INFLUENCE OF FLUID PROPERTIES

RELATED TO THICKNESS OF WEIR CREST

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SUMMARY

The coefficient of discharge for rectangular, thin-plate, full-width weirs can be expressed as a function of h/P alone if the effective-head and effective-width concepts are used to describe the combined effects of viscosity and surface tension. The effective head is defined as the measured head plus (or minus) a constant (k_h) which must be determined by experiment. Kindsvater and Carter, in a report based on a previous research at Georgia Tech, found k_h to be 0.003 ft for full-width weirs covering a wide range of values of h/P. From an analysis of the results of other investigations, they concluded that k_h varied with certain physical characteristics of the equipment, particularly the condition of the weir crest. Subsequently, Shen, in an unpublished study, suggested that k_h is a function of crest thickness. It was the purpose of the writer's research to test the validity of Mr. Shen's hypothesis.

The experimental phase of this investigation involved a carefully controlled, systematic series of tests on eleven different weirs, each having a different crest thickness. The height of the weir, width of the weir, and upstream edge of the weir crest were identical for all tests. The tests consisted primarily of accurate measurements of head and discharge for a full range of discharges as limited by the laboratory supply. Equipment and instrumentation permitted an unusually high order of accuracy in the measurements. (A total of 407 tests are summarized in the Appendix.)

Values of the coefficient of discharge and values of the head-adjustment factor (k_h) computed from the experimental data showed little or no correlation with crest thickness. It was concluded that Mr. Shen's hypothesis was invalid. A comparison of the writer's results with the results of other investigators confirms the conclusion stated by others, that "experiments made by different, capable investigators do not agree, and formulas based on a particular set of data reflect the individual characteristics of those data."

CHAPTER I

INTRODUCTION

Description of the Problem.--The subject of this research is the rectangular, thin-plate, full-width weir. Standard measuring weirs in this category are usually described as "sharp edged," a designation which specifies only that the upstream edge of the crest be sharp. The crest is actually a flat surface, the width of which (hereinafter referred to as the thickness of the crest) is usually required to be from 1/16 to 1/8 in.

Included in the voluminous literature of weirs are experimental data which indicate that the thickness of the crest might have a significant influence on the coefficient of discharge, especially at small values of the head. The implications of this observation generally have been avoided by specifying a narrow range of acceptable values of crest thickness for standard weirs. Nevertheless, data used to support some of the widely used empirical discharge formulas have been obtained from weirs having crest thicknesses varying from "knife edged" to 3/8 in.

It has been suggested that the correlation between crest thickness and coefficient of discharge can be attributed to the influence of fluid viscosity and surface tension. In a report (1)* based on a previous Master's degree thesis, Professor C. E. Kindsvater proposed that the effect of the combined fluid properties be compared to an increase in the

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*Numbers in parenthesis identify items listed under References.

effective head. It was demonstrated that the coefficient of discharge can be expressed in terms of geometric ratios alone if a quantity k_h is added to the measured head to compensate for the effects of viscosity and surface tension. Subsequently, in an unpublished study (2) Shen concluded that the magnitude of k_h was dependent on crest thickness. It is the purpose of this thesis to test the validity of Mr. Shen's conclusion.

Method and Scope of Investigation.--The method used for the investigation involved the experimental determination of the coefficient of discharge for a weir of constant width, constant height, and variable crest thickness. The weir channel, weir plate, and weir crest were constructed with unusual care and precision. Discharges and heads were measured very accurately. Therefore, it is believed that any systematic effect related to changes in crest thickness would have been revealed by variations in the experimentally determined coefficient of discharge.

The weir and weir channel used for the experiments were 1 ft wide. The crest of the weir was 1.5 ft above the floor of the channel. A total of 11 crest thicknesses were tested, varying from "knife edged" to 0.432 in. Heads, as limited by the discharge available, varied from 0.0335 to 1.1437 ft. Water temperatures varied from 65 to 85° F.

Review of the Literature.--The full-width, rectangular weir has received much attention in the technical literature of hydraulics. Among the classic experimental investigations are the works of Francis (3), Bazin (4), Fteley and Stearns (5), and Schoder and Turner (6). Other names, such as

Hamilton Smith, Jr. (7), and Rehbock (8) are associated with widely used formulas. Jameson (9) is the only person known to have attempted a correlation of the results of different experiments on the basis of the crest thickness of the weirs used. One publication (1) and two previous Master's degree theses (10, 11) have been based on research conducted at the Georgia Institute of Technology.

Previous Research at Georgia Tech.--The discharge characteristics of rectangular notch weirs were studied at Georgia Tech by James R. Wells (10) in 1953. The full-width weir was not investigated by Mr. Wells. In 1956, R. W. Carter (11) conducted experiments in a channel of variable width, with weirs of variable height and notch width. Included in his experiments were tests on full-width weirs. The weir crest-plate used both by Mr. Wells and Mr. Carter was a stainless steel plate 1/8 in. thick, with a flat, sharp-edged crest 1/16 in. wide.

The results of Mr. Carter's tests were subsequently included in a comprehensive paper on rectangular, thin-plate weirs published by Kindsvater and Carter (1). In this paper, the concept of "effective head" was applied to Mr. Carter's data as well as the original experimental data of Bazin, Schoder and Turner, and the U. S. Bureau of Reclamation. The procedure was confirmed as a means of isolating the influence of weir and channel geometry from the influence of fluid viscosity and surface tension. Thus, the effects of the fluid properties were apparently compensated for by the constant (k_h) which was computed by successive approximations as the difference between the effective head and the measured head from the experimental data.

CHAPTER II

ANALYSIS OF THE PROBLEM

Dimensional Analysis.--The full-width, rectangular, sharp-edged weir which is the subject of this research can be described in terms of the width of the weir (b), the height of the weir (P), and the thickness of the crest (t). It is assumed that the width of the approach channel is equal to the width of the crest. The fluid properties involved in the discharge function are the specific weight (γ), the density (ρ), the viscosity (μ), and the surface tension (σ). Flow characteristics are the discharge (Q) and the head (h). The head is also involved as a geometric characteristic of the flow pattern. Thus, a complete statement of the discharge function is represented by the equation

$$Q = f(b,\ P,\ t,\ \gamma,\ \rho,\ \mu,\ \sigma,\ h). \tag{1}$$

From this equation, a nondimensional discharge ratio can be expressed as a function of three geometric ratios and two fluid property ratios,

$$\frac{Q}{bh\sqrt{gh}} = f\left(\frac{h}{t},\ \frac{h}{P},\ \frac{h}{b},\ R,\ W\right), \tag{2}$$

in which R and W are the Reynolds (viscosity) and Weber (surface tension) numbers, respectively.

In American engineering practice, the basic equation of discharge for rectangular weirs is

$$Q = Cbh^{3/2}, \tag{3}$$

in which C has the dimensions of $\sqrt{g}$. Thus, from equations (2) and (3),

$$C = \frac{Q}{bh^{3/2}} = f(\frac{h}{t}, \frac{h}{P}, \frac{h}{b}, R, W). \tag{4}$$

<u>Significance of the Geometric Ratios in Equation 4</u>.--The h/t ratio is a non-dimensional measure of the thickness of the crest, which is equivalent to the ratio h/L used to describe the head-width characteristic of broad-crested weirs. In the present instance, however, the h/t ratio is not believed to be significant in the range of values which is involved in the discharge of a truly thin-plate or sharp-edged weir. It is observed that effects which have been assumed to be associated with t are believed to be fluid-property effects. Therefore, they are represented by R and W in equation 4.

The h/b ratio can be described as a shape parameter. On the basis of previous tests (Wells, Carter) it is believed to be insignificant over the full, practical range of the other variables.

The h/P ratio is a primary geometric ratio which is a measure of the depth-contraction characteristic of the weir. The constant, rather large value of P used in the writer's tests imposed a limit on the range of values of h/P involved in this research as compared with the tests made by Wells, Carter, and others.

<u>Significance of R and W in Equation 4</u>.--The Reynolds number, R, is a measure of the relative influence of viscosity. It is defined by the ratio

$$R = \frac{VL\rho}{\mu} = \frac{VL}{\nu}, \tag{5}$$

in which V is a typical velocity, L is a significant length, and ν is the kinematic viscosity of the liquid. For any weir operating under a small head, a significant length is the head; for narrow weirs, a significant length is the width; and, for thick-crested weirs, a significant length is the thickness of the crest. Thus, for weirs in general, there are at least three possible forms of the Reynolds number, all of which are independently related to the influence of viscosity on the coefficient of discharge.

The Weber number, W, is a measure of the relative influence of surface tension. It is defined by the ratio,

$$W = \frac{V\sqrt{L}}{\sqrt{\sigma/\rho}} \tag{6}$$

in which V is a typical velocity, L is a significant length, σ is the surface tension, and ρ is the density of the liquid. Here, too, possibly significant lengths include the head, the width of the weir, and the thickness of the crest. Thus, there are three possible forms of the Weber number just as there are three possible forms of the Reynolds number.

For a given weir, the velocity V in equations 5 and 6 is proportional to $\sqrt{h}$. For a given liquid, ν, σ, and ρ are essentially constant in the normal temperature range. The effects of both viscosity and surface tension have been related to the magnitudes of h, b, and t. Therefore, it is impossible to distinguish the separate effects of the two fluid properties from experiments on a single liquid.

From the foregoing discussion of the significance of the ratios in equation 4, it is concluded that t/h and h/b can be excluded and, for tests on a single liquid, R and W can be effectively replaced by the absolute magnitudes of h, b, and t. Thus, for the experiments made for this research,

$$C = f(\frac{1}{p}, h, b, t). \tag{7}$$

Of the independent variables in equation 7, only b was held constant in the experiments.

Evaluation of the Influence of Viscosity and Surface Tension.--The principal effects of viscosity on weir flow are those which are associated with flow pattern modifications due to boundary resistance and separation. The effects of surface tension are associated with the force due to surface tension and the flow pattern modification due to "clinging" on the crest. A detailed description and discussion of these effects (exclusive of effects related to variable crest thickness) are features of the Kindsvater-Carter paper (1). The following pertinent observations are abstracted from that paper:

1. The combined effects of viscosity and surface tension on a weir of constant crest thickness can be likened to an increase in head and (for full-weirs) a decrease in the width of the weir.
2. The coefficient of discharge can be expressed in terms of geometric ratios alone if the effects of viscosity and surface tension are accounted for by an adjustment of measured values of h and b.
3. The adjustment of h and b can be accomplished very simply with

the equations

$$h_e = h + k_h \tag{8}$$

and

$$b_e = b + k_b, \tag{9}$$

in which h_e and b_e are defined as the "effective" values of head and width, respectively, and k_h and k_b are quantities which must be determined by experiment.

4. Use of the effective head and effective width results in a modified general discharge equation,

$$Q = C_e b_e h_e^{3/2}, \tag{10}$$

in which C_e is truly a function of h/P alone,

$$C_e = f(h/P), \tag{11}$$

if the fluid property effects are properly accounted for with the adjustment factors k_h and k_b.

From experiments on notch weirs covering a full range of values of h, b, h/P, and b/B (where B is channel width upstream from a notch weir), Kindsvater and Carter concluded that k_h is a constant for a given weir, but that k_b is a function of b/B. From their experiments on full-width weirs, k_b is a constant (-0.003 ft) for all values of the other independent variables.

Values of k_h determined from tests performed by different experimenters indicated that the head adjustment factor varies with certain physical details of the experimental set-up. Thus, whereas k_h was 0.003 to 0.004 ft for the Georgia Tech (Carter), Schoder and Turner, and Bureau of Reclamation tests, it was determined to be 0.012 ft for the Bazin tests. The larger value of k_h for the Bazin tests was attributed to the fact that Bazin's weir is generally believed to have been somewhat less than sharp-edged and "thin." However, it is also significant that Bazin's weir crest was considerably thicker (0.276 in.) than that used by the other investigators.

Additional evidence of an independent correlation between k_h and t was discovered by Shen (2) in connection with his reanalysis of published experimental data on triangular weirs. Furthermore, on the basis of the data available to him, Shen concluded that values of k_h for rectangular and triangular weirs were commensurate. Thus, he plotted a curve, shown here as figure 1, which appeared to substantiate the assumed relationship between k_h and t. As indicated in the figure, some of the values plotted were obtained from tests on rectangular weirs. Others were obtained from tests on triangular weirs.

The purpose of the writer's research was to test the validity of the relationship shown on figure 1. The basis for the validity test is a systematic experimental investigation of the influence of crest thickness on a single kind of weir.

CHAPTER III

EXPERIMENTAL EQUIPMENT

General.--All experiments made for this investigation were made in the Hydraulics Laboratory, School of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia. Water was supplied to the flume from the laboratory's constant-head system. A gate valve in the supply pipe was used to control the discharge. The nappe was fully ventilated and unsubmerged. The general arrangement of the equipment is shown in figure 2.

The Experimental Channel.--A one-foot-wide experimental channel was constructed within an existing, permanent, steel-and-glass flume which is 3 ft wide, 3 ft deep, and approximately 30 ft long from the entrance baffles to the tailgate. The walls of the experimental channel in the vicinity of the weir were made of 1/4 in. aluminum plate, which was fastened to the floor and walls of the flume with structural angles and steel rods. Wall braces were used as necessary to produce a rigid channel with plane, smooth, vertical, and parallel walls. Upstream from the aluminum-plate walls, which extended 5 ft upstream from the weir, the channel walls were made of 3/4 in. exterior-grade plywood. Steel sheets which were rolled in the form of a quadrant of a circular cylinder were attached to the upstream end of the wooden walls to provide a streamlined entrance to the experimental channel. At the weir, the aluminum wall plates were made to project past the weir plate a distance of 4 in.

The bottom of the projection was at the level of the weir crest. Figures 2 and 3 show the experimental channel and weir in the flume.

Great care was taken to produce a uniform velocity distribution at the entrance to the experimental channel. Devices used to accomplish this included a complex of baffles and screens in the forebay of the flume and a surface float in the experimental channel at the entrance. Velocity distributions in the channel were measured with a standard U.S.G.S. Pygmy current meter. The results of a typical measurement with the final baffle and float arrangement are shown in table 1. The velocity distribution was checked periodically throughout the investigation.

The Weir.--The basic weir bulkhead was a 1/4-in. thick aluminum plate which was bolted to the floor and frame of the flume and the walls of the experimental channel. The crest was a bar of laminated brass strips which was bolted to the top of the bulkhead. To make the crest, strips were sawed from a sheet of polished brass approximately 0.024 in. thick. A number of the strips aggregating about 1/2 in. thickness were then laminated under pressure with a "Lucite" plastic cement. After the cement was allowd to harden for several days, the laminated bar was clamped on the flat bed of a tool-maker's high-speed grinder, and one edge was cut down to a smooth, plane surface with a carbide-tipped blade. This surface was the top surface of the weir crest.

Before the bar was attached to the weir plate, several of the laminae were stripped from the face of the bar which was intended to become the upstream face of the crest. The result was to produce an ideally sharp, square upstream edge. The bar was then bolted to the weir plate.

Thereafter, as the tests proceeded, the crest was made successively thinner by stripping additional laminae from the downstream face of the bar. The stripping process did not require that the bar be removed from the weir plate. Thus, it was possible to change the thickness of the crest without disturbing or even touching the critical upstream face and edge of the crest. The method used to construct the weir crest is believed to be ideally suited to the purpose of this research. Figure 4 is a close-up of the weir crest in the test set-up. Figure 5 shows a lamina being stripped from the crest to change its thickness.

The weir crest used for the last test series (number 11) was "knife edged." To produce this crest, the last remaining lamina of the crest bar was filed to a knife edge with the strip in place on the weir bulkhead. The crest strip was "backed up" with a straight edge in order to provide rigidity during the filing process. A very fine-tooth file was used, and the filing was done by an experienced laboratory technician. All of the filing was done on the downstream edge of the crest strip. Thus, the upstream face remained plane and smooth.

Dimensional Measurements.--Weir dimensions which had to be measured very accurately are the width of the weir (that is, the width of the channel in the plane of the weir) and the thickness of the crest. Much less critical is the height of the weir, which is measured with respect to the level of the bottom of the experimental channel. It is sufficiently accurate for all purposes to take the height of the weir to be 1.5 ft.

The width of the weir was measured with an inside micrometer. The value used as b in all computations was determined as the average of measurements made at 6 equally spaced vertical positions on each of 3 sections. One section was in the plane of the upstream face of the weir crest. The other two were located in planes which were 1.5 in. upstream and downstream, respectively, from the plane of the weir. A typical, complete set of measurements to determine b is shown in table 2. The average value of b obtained from these measurements was 1.000 ft. The width of the crest was checked periodically, but the measurements did not vary appreciably from the values shown in table 2.

The thickness of the crest was measured with a micrometer caliper. The value used as t in the analysis of the experimental data is the average of 5 measurements made at the ends, middle, and quarter points of the crest. Measurements were made before and after each test series, and the results are summarized in table 3.

Headwater Measurements.--The headwater level was measured with a zero-displacement manometer which was mounted on the frame of the flume. The manometer was connected to a pair of piezometers located opposite each other in the aluminum-plate walls of the experimental channel. The piezometers, as shown in figure 2, were 1 ft above the floor and 3.5 ft upstream from the weir plate. The manometer was zeroed to the crest of the weir by means of an engineer's level and a special target rod. Figure 6 is a close-up photograph of the back-lighted needle point and stilling well which are significant features of the manometer.

Discharge Measurements.--Discharges were measured with the laboratory's semi-automatic weighing-tank system. The overall accuracy of the equipment is believed to be such that the discharge measurements are at least correct to the nearest one-half of one per cent. A general view of the downstream end of the flume and the weighing tank is shown in figure 7.

CHAPTER IV

EXPERIMENTAL PROCEDURE AND RESULTS

Experimental Procedure.--The primary purpose of the writer's tests was to evaluate the influence of weir-crest thickness in terms of effects which have been attributed to the influence of viscosity and surface tension. It was anticipated that those effects would be revealed by an independent but different correlation between C and h for each crest thickness tested. Therefore, the standard test procedure used for the 11 test series (table 3) involved the measurement of discharge and head for a full range of heads as limited by the available flow.

Initial tests indicated an apparent correlation between C and the test sequence; that is, C appeared to depend somewhat on whether the discharge was being increased or decreased during the test sequence. However, it was also demonstrated that, at the lower values of h, tests made at different times, regardless of sequence, would give different values of C. This led to the assumption that the differences in C could be related to changes in temperature or changes in the experimental equipment, including the cleanliness of the crest. Consequently, the test procedure was modified to include frequent, regular inspection for leaks or changes in dimension; cleaning of the baffles at the entrance to the test channel; cleaning of the crest with carbon tetrachloride; flushing of the manometer; and measurement of water temperature with a thermometer permanently located at the entrance to the channel.

The total effect of these precautions was to decrease but not to prevent a variation in values of C at lower values of h. It is emphasized that the larger variations were associated with differences in the time of observation. Thus, a complete series of measurements made over a period of several days was more likely to show a considerable disparity in low-head values of C than was a series which was completed in a single day.

Experimental Results.--A summary of the results of the experiments is shown in tables 4 to 14, inclusive. Heads and discharges shown are the average of several measurements. Temperatures were measured at the beginning, middle, and end of each run. Values of the specific weight of water used to convert weight measurements to discharge were determined from a chart which took into account local gravity as well as temperature. The width of the weir (b) was taken to be 1.000 ft, and the height of the weir was taken to be 1.5 ft for all tests.

Values of C shown in tables 4 through 14 were computed with the equation,

$$C = \frac{Q}{bh^{3/2}} , \tag{4}$$

in which Q, b, and h are the unadjusted, measured values. Values of $C_e{}'$ were computed from the equation

$$C_e{}' = \frac{Q}{bh_e{}^{3/2}} , \tag{12}$$

in which

$$h_e = h + k_h \tag{8}$$

is the adjusted "effective" head, but b is the measured value of weir width. Values of k_h used to compute h_e are shown as a footnote in the summary tables. The procedure used to evaluate k_h is explained below.

CHAPTER V

ANALYSIS AND DISCUSSION OF RESULTS

Influence of h on C.--Figures 8 to 12, inclusive, show values of C plotted as a function of h for five series of tests which cover the full range of crest thicknesses tested. The curves show a characteristic minimum value of C at a head of about 0.2 ft, with higher values at both smaller and larger heads. Maximum scatter of the plotted points occurs at the smaller heads. This scatter is believed to be caused partly by the fact that the relative accuracy of the measurements decreases as h decreases. It is also caused partly by the small, unexplained changes which occurred during the period required to complete the test on a given weir. Actually, in terms of relative accuracy, the average deviations from a mean curve are not excessive.

The positive slope of the curves (figures 8 through 12) at heads greater than about 0.2 ft is indicative of the normal relationship between C and h/P. In fact, because P is a constant for all the tests, plots of C versus h/P would be similar to the corresponding plots of C versus h shown in these figures.

The negative slope of the curves at heads less than 0.2 ft is generally believed to be related to the influence of viscosity and surface tension, the effects of which have been compared with the effects of an increase in head. The influence of the fluid properties is present at all heads, of course, but the relative effect increases as head decreases, and it is appreciable only at the very small values of h.

Evaluation of k_h and C_e'.--In the Kindsvater-Carter paper (1) it is demonstrated that the fluid-property influence can be effectively "removed" from the coefficient of discharge by an empirical procedure which makes use of the effective-head concept (equation 8). The result is a coefficient, C_e, which is a function of h/P alone (equation 11). For the writer's tests, an alternative coefficient, C_e', was defined in equation 12. This coefficient is similar to C_e except that it involves the measured width instead of the effective width. Because b was a constant in these tests, k_b could not be evaluated. If the results of Carter's tests are used, the influence of k_b for b = 1.0 ft is equivalent to a difference of approximately 0.3 per cent between C_e and C_e'. This almost negligible difference is not significant in relation to the principal research objective -- that is, to determine whether an independent correlation exists between k_h and crest thickness.

The quantity k_h was evaluated from the experimental data by a trial procedure. For a series of tests in which h was the principal variable, k_h was determined by successive approximations as the quantity which would effectively eliminate any correlation between C_e' and h in a plot of experimental data showing C_e' as a function of h/P. In the Kindsvater-Carter paper, the process is very effectively illustrated with figures based on the Schoder and Turner and Bazin data. It was also demonstrated in that paper that the relationship between C_e and h/P is conveniently approximated by an equation of the straight-line form. Thus, an incidental criterion for the evaluation of k_h is a straight-line relationship between C_e' and h/p.

Figures 13 through 23 show the results of the computations which resulted in the determination of k_h and $C_e{}'$ for each of the 11 weirs (that is, 11 crest thicknesses) tested by the writer. The straight-line curves shown on the figures were fitted visually to the plotted points. All the curves are shown for comparison on figure 24. Figure 25 shows $C_e{}'$ as a function of t for two values of h/P. The values plotted on figure 25 were read from the straight line curves on figures 13 through 23.

It is apparent from figures 24 and 25 that $C_e{}'$ is virtually independent of crest thickness in the range of values usually specified for standard weirs. In fact, if the curve for test series 1 (t = 0.432 in.) is excluded, the remaining curves on figure 24 show a maximum difference of about 0.3 per cent (in terms of $C_e{}'$) over the full range of values of h/P tested. Thus, the average deviation from the mean shown by the curves in figure 25 corresponds to an order of accuracy which is much higher than that which is ordinarily expected of weirs. It is emphasized, however, that the curves shown in figure 25 are based on the "best-fit" values of k_h; that is, values of k_h which were determined by successive approximations to give the best-fitting straight line curves in figures 13 through 23.

A comparison of the results of tests made on the series 11 weir (knife-edged) with the results of tests made on the series 1 to 10 weirs indicates that the "clinging" phenomenon associated (1) with flat-topped crests is of negligible significance.

<u>Relation between k_h and t</u>.--Values of k_h used for the curves shown in figure 25 varied from 0.0025 to 0.0040 ft. These values are plotted as a function of t in figure 26. The results show little or no correlation between k_h and t. Also shown in figure 26 is the curve suggested by Shen (figure 1). It is apparent that the writer's tests do not confirm Mr. Shen's hypothesis.

The different values of k_h determined for the different weirs tested is believed to indicate slight, nonreproducible differences in physical details of the weir or weir channel. This leads to the conclusion that, for practical purposes, a constant value of k_h could be used for the full range of values of t covered by the writer's experiments. The effect of using a constant, average value of k_h is shown in figure 27. Here $C_e{}'$, computed on the basis of k_h = 0.0030 ft for all tests, is shown as a function of h/P. The curves in the figure are comparable with the curves in figure 24. The spread in values of $C_e{}'$ shown in figure 27 is a maximum at small values of h/P. This is consistent with the observation that the experimental error and the effects of small differences in physical details increase as h decreases. Over the full range of values of h/P shown in figure 27, the average deviation from a mean curve is almost twice that shown in figure 24. However, deviation is still well within the limits of accuracy expected of standard weirs.

<u>Comparison with other Investigators</u>.--The thickness of the crest of the weir used in the Wells and Carter tests was nominally 1/16 or 0.062 in. The nearest equivalent among the writer's weirs was the weir used for

test series 8 ($t = 0.072$ in.). In order to compare the results of the tests on the two weirs, values of C_e' obtained from test series 8 were adjusted to obtain values of C_e, using $k_b = -0.0030$ ft from the results of Mr. Carter's tests. The comparison is shown in figure 28. Also shown are curves based on the Schoder and Turner tests and the 1929 Rehbock formula, which are described in reference (1).

Figure 28 shows that, in comparison with all the other curves, the curve based on the writer's tests gives lower values of C_e at small values of h/P and higher values of C_e at larger values of h/P. The maximum difference between Mr. Carter's curve and the writer's curve is about 1 per cent. This comparison is believed to be additional evidence to support the statement, "...... the results of experiments made by different, capable investigators do not agree, and formulas based on a particular set of data reflect the individual characteristics of those data. For this reason, too, a truly reproducible, standard measuring weir and a precise, universal discharge formula are impractical" (1).

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A P P E N D I X

Table 1. Velocity Distribution in the Experimental Channel*

Depth below Water Surface (ft)	Velocity (fps)		
	Section 1	Section 2	Section 3
0.168	1.49	1.40	1.41
0.368	1.50	1.44	1.40
0.568	1.46	1.45	1.44
0.768	1.44	1.44	1.44
0.968	1.43	1.46	1.46
1.168	1.48	1.50	1.54
1.368	1.49	1.51	1.56
1.568	1.48	1.51	1.59
1.768	1.44	1.50	1.55
1.968	1.50	1.52	1.55
2.168	1.56	1.55	1.55
2.368	1.52	1.52	1.50

*All measurements made at a station 9 ft upstream from the weir. Looking downstream, section 1 is 2 in. from left wall, section 2 is on centerline, and section 3 is 2 in. from right wall. Discharge is 3.92 cfs, corresponding to head of 1.07 ft.

Table 2. Measurement of Flume Width (b).

Distance above Crest Level (in.)	Distance between Channel Walls (in.)*					
	Station 1		Station 2		Station 3	
	A	B	A	B	A	B
1	12.002	12.003	11.997	11.997	11.998	11.997
3	11.994	11.996	11.989	11.989	11.998	11.987
5	11.992	11.991	11.986	11.985	11.985	11.985
7	11.996	11.998	11.991	11.991	11.991	11.992
9	12.006	12.008	12.000	12.000	12.000	12.000
11	12.002	12.003	12.000	12.001	12.006	12.006

*Station 2 is in the plane of the upstream face of the crest; station 1 is 1.5 in. upstream from station 2, and station 3 is 1.5 in. downstream from station 2. (A) indicates flume is empty, and (B) indicates flume is filled to level of crest during measurement. Value of b determined from these measurements ≑ 11.995 in. or 1.000 ft.

Table 3. Measurement of Crest Thickness (t)

Test Series	Thickness of Weir Crest (in.)* Left End	Quarter Pt.	Center	Quarter Pt.	Right End	Average t
1	0.4308 0.4313	0.4322 0.4321	0.4327 0.4325	0.4310 0.4310	0.4316 0.4315	0.432
2	0.3580 0.3581	0.3592 0.3591	0.3601 0.3600	0.3597 0.3600	0.3581 0.3580	0.359
3	0.2865 0.2865	0.2875 0.2872	0.2885 0.2880	0.2870 0.2871	0.2880 0.2872	0.287
4	0.2155 0.2150	0.2155 0.2162	0.2165 0.2162	0.2155 0.2150	0.2155 0.2155	0.215
5	0.1672 0.1669	0.1684 0.1682	0.1681 0.1683	0.1670 0.1670	0.1680 0.1679	0.168
6	0.1195 0.1198	0.1207 0.1213	0.1200 0.1210	0.1193 0.1198	0.1200 0.1206	0.120
7	0.0962 0.0959	0.0966 0.0968	0.0963 0.0960	0.0959 0.0958	0.0967 0.0969	0.096
8	0.0718 0.0716	0.0722 0.0722	0.0717 0.0721	0.0710 0.0718	0.0722 0.0722	0.072
9	0.0480 0.0482	0.0482 0.0483	0.0478 0.0478	0.0471 0.0471	0.0480 0.0481	0.048
10	0.0240 0.0241	0.0233 0.0233	0.0233 0.0233	0.0230 0.0231	0.0228 0.0227	0.023
11	(Knife edged)					

*Average of measurements made before and after the test series.

Table 4. Summary of Test Results, Test Series 1*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
1	77.0	0.5370	0.358	1.333	3.388	3.360
2	77.0	0.4817	0.321	1.127	3.371	3.336
3	77.0	0.4300	0.287	0.946	3.353	3.319
4	77.0	0.3692	0.246	0.748	3.331	3.294
5	77.5	0.3051	0.203	0.558	3.310	3.263
6	78.0	0.2408	0.160	0.389	3.288	3.224
7	78.0	0.1615	0.108	0.214	3.301	3.195
8	78.0	0.1013	0.068	0.107	3.315	3.191
9	78.0	0.0905	0.060	0.0906	3.325	3.146
10	78.0	0.0820	0.055	0.0785	3.340	3.165
11	78.0	0.0770	0.051	0.0715	3.343	3.165
12	78.0	0.0698	0.047	0.0634	3.441	3.218
13	78.0	0.0650	0.043	0.0555	3.340	3.133
14	78.0	0.0720	0.048	0.0674	3.492	3.287
15	78.0	0.1110	0.074	0.126	3.404	3.272
16	78.0	0.2008	0.134	0.299	3.329	3.252
17	78.0	0.2700	0.180	0.467	3.326	3.272
18	79.0	0.3770	0.251	0.774	3.345	3.306
19	79.0	0.5560	0.377	1.407	3.393	3.367
20	79.0	0.6360	0.424	1.736	3.422	3.398
21	79.0	0.7626	0.508	2.305	3.461	3.438
22	79.0	0.8850	0.590	2.921	3.508	3.490
23	79.0	0.1760	0.117	0.243	3.287	3.209
24	79.0	0.1077	0.072	0.118	3.327	3.179
25	79.0	0.1532	0.102	0.200	3.334	3.248
26	79.0	0.1132	0.075	0.128	3.362	3.243
27	79.0	0.1335	0.089	0.162	3.313	3.192
28	79.0	0.2005	0.134	0.296	3.296	3.212
29	80.0	0.2805	0.187	0.492	3.308	3.246
30	80.0	0.4035	0.269	0.856	3.341	3.298
31	80.0	1.0570	0.705	3.872	3.563	3.548

*t = 0.432 in., k_h = 0.0030 ft.

Table 5. Summary of Test Results, Test Series 2*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C'_e
1	79.0	0.0940	0.063	0.0952	3.307	3.153
2	79.0	0.1030	0.069	0.109	3.292	3.158
3	79.5	0.1725	0.115	0.235	3.280	3.187
4	79.5	0.2648	0.177	0.448	3.291	3.233
5	79.5	0.3335	0.223	0.638	3.312	3.262
6	80.0	0.4350	0.290	0.954	3.325	3.292
7	80.0	0.5440	0.363	1.351	3.367	3.339
8	80.0	0.6520	0.435	1.794	3.408	3.384
9	79.5	0.7630	0.509	2.292	3.439	3.419
10	79.0	0.8743	0.583	2.848	3.484	3.468
11	79.0	0.9787	0.562	3.408	3.520	3.502
12	79.0	1.1190	0.746	4.229	3.573	3.558
13	78.0	0.4553	0.304	1.029	3.348	3.319
14	78.0	0.6705	0.447	1.877	3.420	3.393
15	78.0	0.5480	0.365	1.368	3.373	3.346
16	77.5	0.3550	0.237	0.707	3.340	3.300
17	77.5	0.2910	0.194	0.524	3.340	3.289
18	77.5	0.2330	0.155	0.374	3.326	3.265
19	77.5	0.1520	0.101	0.197	3.326	3.233
20	77.5	0.0968	0.064	0.0982	3.262	3.109
21	78.0	0.0800	0.053	0.0742	3.284	3.105
22	79.0	0.0920	0.061	0.0942	3.375	3.214
23	79.0	0.1360	0.091	0.166	3.297	3.196
24	79.0	0.2082	0.139	0.312	3.286	3.219
25	79.0	0.3115	0.208	0.574	3.299	3.244
26	79.0	0.4370	0.291	0.965	3.339	3.305
27	79.5	0.5903	0.394	1.529	3.370	3.344
28	79.5	0.5908	0.514	1.531	3.437	3.416
29	79.5	0.7708	0.394	2.326	3.370	3.348
30	79.5	0.8855	0.590	2.893	3.472	3.451

*t = 0.359 in., k_h = 0.0030 ft.

Table 6. Summary of Test Results, Test Series 3*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C'_e
1	78.5	0.1010	0.067	0.107	3.334	3.170
2	78.5	0.1380	0.092	0.169	3.293	3.175
3	79.0	0.2022	0.135	0.300	3.304	3.219
4	79.0	0.2900	0.193	0.516	3.305	3.247
5	79.5	0.3905	0.260	0.812	3.327	3.283
6	79.5	0.4952	0.330	1.169	3.356	3.320
7	79.5	0.6272	0.418	1.683	3.388	3.360
8	79.5	0.7450	0.497	2.208	3.434	3.410
9	79.5	0.8732	0.582	2.838	3.478	3.456
10	79.5	0.9932	0.662	3.477	3.513	3.494
11	79.5	1.1017	0.734	4.112	3.556	3.539
12	79.5	0.9183	0.612	3.075	3.494	3.474
13	79.5	0.6865	0.458	1.947	3.423	3.396
14	79.0	0.5135	0.342	1.240	3.369	3.335
15	79.0	0.2710	0.181	0.468	3.315	3.253
16	79.0	0.1820	0.121	0.255	3.284	3.193
17	79.0	0.1135	0.076	0.128	3.347	3.241
18	79.0	0.0805	0.054	0.0772	3.387	3.178
19	79.0	0.0627	0.042	0.0538	3.427	3.156
20	79.0	0.0580	0.039	0.0484	3.456	3.173
21	79.0	0.0815	0.054	0.0798	3.432	3.217
22	79.0	0.1470	0.098	0.188	3.341	3.226
23	79.0	0.1463	0.098	0.186	3.319	3.204
24	78.5	0.1175	0.078	0.135	3.345	3.205
25	79.0	0.1480	0.099	0.189	3.308	3.195
26	79.0	0.2072	0.138	0.313	3.319	3.238
27	78.0	0.1615	0.108	0.217	3.344	3.236
28	78.0	0.2250	0.150	0.354	3.314	3.239
29	78.0	0.3035	0.203	0.557	3.331	3.237
30	79.0	0.4310	0.287	0.947	3.348	3.236
31	79.0	0.5350	0.357	1.317	3.365	3.335
32	79.0	0.3328	0.222	0.637	3.314	3.253
33	79.0	0.2018	0.135	0.297	3.279	3.151

*t = 0.287 in., k_h = 0.0035 ft.

Table 7. Summary of Test Results, Test Series 4*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
1	77.0	0.0700	0.047	0.0628	3.396	3.157
2	77.0	0.0930	0.062	0.0950	3.344	3.171
3	77.0	0.1392	0.093	0.171	3.290	3.167
4	77.0	0.1960	0.131	0.284	3.275	3.190
5	77.0	0.2793	0.186	0.486	3.289	3.228
6	77.0	0.3445	0.230	0.668	3.305	3.256
7	76.5	0.4492	0.301	1.006	3.341	3.303
8	76.0	0.5505	0.367	1.376	3.369	3.337
9	75.0	0.6732	0.449	1.885	3.412	3.386
10	75.0	0.8075	0.538	2.505	3.451	3.429
11	74.5	0.9565	0.638	3.272	3.498	3.479
12	74.0	1.1023	0.735	4.118	3.558	3.542
13	73.5	0.8765	0.591	2.856	3.481	3.460
14	73.5	0.7288	0.486	2.137	3.435	3.410
15	73.0	0.5720	0.381	1.470	3.399	3.368
16	73.0	0.3922	0.261	0.826	3.363	3.319
17	73.0	0.2455	0.164	0.407	3.345	3.274
18	73.0	0.1792	0.119	0.251	3.309	3.217
19	73.0	0.0950	0.063	0.0987	3.369	3.189
20	73.0	0.0560	0.037	0.0468	3.516	3.225
21	73.0	0.0525	0.035	0.0426	3.536	3.228
22	74.0	0.1615	0.108	0.212	3.275	3.170
23	75.0	0.2340	0.156	0.373	3.293	3.220
24	75.0	0.3123	0.208	0.579	3.321	3.265
25	75.0	0.4030	0.269	0.853	3.334	3.291
26	75.0	0.5095	0.340	1.221	3.358	3.324
27	75.5	0.6215	0.414	1.667	3.402	3.374
28	75.5	0.1500	0.100	0.194	3.338	3.227
29	75.5	0.1007	0.067	0.107	3.353	3.188
30	75.5	0.1430	0.095	0.180	3.333	3.214
31	75.5	0.2060	0.137	0.311	3.324	3.243
32	74.5	0.1330	0.089	0.163	3.362	3.239
33	74.5	0.2260	0.151	0.358	3.329	3.255
34	74.5	0.3187	0.212	0.602	3.344	3.291
35	74.5	0.4752	0.317	1.106	3.375	3.338
36	74.5	0.6408	0.427	1.749	3.409	3.381

(continued)

Table 7. Summary of Test Results, Test Series 4* (continued)

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
37	74.5	0.8117	0.541	2.519	3.451	3.423
38	74.5	0.9720	0.648	3.363	3.510	3.491
39	72.0	0.0960	0.064	0.102	3.406	3.232
40	73.5	0.0905	0.060	0.0922	3.383	3.201
41	72.5	0.1260	0.084	0.145	3.341	3.212
42	73.0	0.1780	0.119	0.249	3.310	3.216
43	73.0	0.2492	0.166	0.413	3.321	3.250
44	73.5	0.3560	0.237	0.710	3.344	3.295
45	74.0	0.2750	0.183	0.480	3.325	3.262
46	74.0	0.2015	0.134	0.302	3.336	3.251
47	74.0	0.1300	0.086	0.157	3.343	3.213
48	74.5	0.2512	0.167	0.420	3.333	3.265
49	74.5	0.4270	0.285	0.936	3.355	3.314
50	74.5	0.1675	0.112	0.228	3.325	3.226
51	73.0	0.1645	0.110	0.220	3.303	3.202
52	73.0	0.2352	0.157	0.378	3.312	3.242
53	73.0	0.3112	0.207	0.579	3.336	3.280
54	73.0	0.1430	0.095	0.180	3.323	3.205
55	73.0	0.1425	0.095	0.179	3.334	3.222
56	70.5	0.3040	0.203	0.561	3.349	3.292
57	70.5	0.5498	0.367	1.380	3.386	3.354
58	71.0	0.7197	0.480	2.097	3.434	3.409
59	71.0	0.9000	0.600	2.976	3.486	3.466
60	71.0	1.0530	0.702	3.820	3.536	3.518
61	71.0	1.1102	0.740	4.164	3.559	3.543
62	71.0	0.0837	0.056	0.0828	3.416	3.213
63	71.0	0.0733	0.049	0.0686	3.461	3.217
64	71.0	0.0745	0.050	0.0698	3.428	3.200
65	71.0	0.0683	0.046	0.0614	3.448	3.197

*t = 0.215 in., k_h = 0.0035 ft.

Table 8. Summary of Test Results, Test Series 5*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
1	70.0	0.0628	0.042	0.0564	3.585	3.261
2	70.0	0.0818	0.055	0.0802	3.429	3.184
3	70.0	0.1030	0.069	0.112	3.385	3.201
4	71.0	0.1383	0.092	0.172	3.342	3.214
5	71.0	0.2350	0.157	0.380	3.329	3.249
6	71.0	0.3142	0.209	0.591	3.354	3.295
7	71.0	0.3925	0.262	0.827	3.361	3.305
8	71.0	0.4800	0.320	1.121	3.373	3.331
9	71.0	0.5598	0.373	1.423	3.399	3.361
10	71.0	0.6477	0.432	1.781	3.417	3.383
11	71.0	0.7265	0.484	2.128	3.437	3.405
12	71.0	0.8272	0.551	2.614	3.474	3.451
13	71.0	0.9300	0.620	3.145	3.507	3.485
14	71.0	1.0245	0.683	3.670	3.539	3.516
15	71.0	0.2390	0.159	0.388	3.316	3.236
16	71.5	0.3695	0.246	0.746	3.321	3.263
17	71.5	0.7493	0.500	2.227	3.433	3.408
18	71.5	0.9972	0.665	3.501	3.516	3.496
19	71.0	1.1200	0.747	4.218	3.559	3.540
20	67.5	0.1728	0.115	0.242	3.366	3.248
21	68.0	0.2373	0.158	0.385	3.330	3.255
22	68.0	0.3198	0.213	0.604	3.341	3.277
23	68.0	0.4310	0.287	0.950	3.356	3.310
24	68.0	0.5300	0.353	1.302	3.376	3.338
25	68.0	0.6193	0.413	1.657	3.399	3.369
26	68.0	0.7712	0.514	2.332	3.443	3.418
27	68.0	0.8690	0.579	2.815	3.475	3.451
28	68.0	0.9535	0.636	3.269	3.511	3.486
29	68.0	1.0515	0.701	3.819	3.542	3.519
30	68.0	1.1280	0.752	4.271	3.566	3.547
31	67.0	0.0975	0.065	0.102	3.349	3.129
32	67.5	0.1415	0.094	0.179	3.352	3.199
33	67.5	0.2120	0.141	0.326	3.341	3.248
34	67.5	0.2890	0.193	0.517	3.329	3.262
35	67.5	0.0850	0.057	0.0855	3.448	3.227
36	67.5	0.1375	0.092	0.171	3.346	3.192

(continued)

Table 8. Summary of Test Results, Test Series 5* (continued)

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
37	67.5	0.1745	0.116	0.244	3.340	3.217
38	68.0	0.6717	0.448	1.887	3.429	3.396
39	68.0	0.9215	0.614	3.097	3.501	3.476
40	68.0	0.3650	0.243	0.738	3.346	3.293
41	68.0	0.0692	0.046	0.0631	3.469	3.201
42	66.0	0.1147	0.076	0.132	3.408	3.222
43	66.0	0.3015	0.201	0.556	3.355	3.281
44	66.0	0.4877	0.325	1.151	3.379	3.335
45	66.5	0.6467	0.431	1.778	3.419	3.384
46	66.5	0.8047	0.536	2.507	3.473	3.446
47	66.5	0.9615	0.641	3.320	3.521	3.497
48	66.5	1.1082	0.739	4.163	3.568	3.550
49	67.0	0.7085	0.472	2.045	3.429	3.397
50	67.0	0.1693	0.113	0.231	3.314	3.208
51	67.0	0.2592	0.173	0.439	3.324	3.251
52	67.0	0.3185	0.212	0.598	3.327	3.258
53	67.0	0.4887	0.326	1.149	3.363	3.319
54	67.0	0.6432	0.429	1.757	3.406	3.376
55	67.0	0.8048	0.537	2.494	3.454	3.428
56	67.0	0.1338	0.089	0.164	3.350	3.200

*t = 0.168 in., k_h = 0.0040 ft.

Table 9. Summary of Test Results, Test Series 6*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
1	67.5	0.0607	0.040	0.0519	3.465	3.188
2	67.5	0.0650	0.043	0.0570	3.435	3.185
3	67.5	0.0682	0.045	0.0616	3.465	3.212
4	68.0	0.0722	0.048	0.0670	3.455	3.212
5	68.0	0.0797	0.053	0.0760	3.380	3.168
6	68.0	0.1055	0.070	0.115	3.341	3.179
7	68.0	0.1465	0.098	0.186	3.322	3.208
8	68.0	0.1888	0.126	0.272	3.312	3.223
9	68.5	0.2445	0.163	0.403	3.330	3.260
10	68.5	0.3115	0.208	0.580	3.337	3.281
11	69.0	0.3862	0.257	0.804	3.350	3.305
12	69.0	0.4780	0.319	1.114	3.371	3.334
13	69.0	0.5520	0.368	1.393	3.395	3.363
14	69.0	0.6398	0.427	1.748	3.415	3.388
15	69.0	0.7290	0.486	2.140	3.439	3.414
16	69.0	0.8258	0.551	2.600	3.464	3.442
17	69.0	0.9177	0.612	3.071	3.493	3.473
18	69.0	1.0075	0.672	3.572	3.532	3.514
19	69.0	1.1035	0.736	4.131	3.564	3.547
20	69.0	0.1305	0.087	0.157	3.339	3.207
21	69.5	0.1830	0.122	0.262	3.345	3.252
22	69.5	0.1815	0.121	0.257	3.327	3.233
23	69.5	0.2908	0.194	0.522	3.330	3.271
24	70.0	0.4393	0.293	0.977	3.356	3.316
25	70.0	0.5852	0.390	1.523	3.401	3.371
26	69.5	0.7857	0.524	2.410	3.459	3.437
27	69.0	0.9590	0.639	3.302	3.516	3.497
28	68.5	1.1437	0.762	4.384	3.584	3.568

*t = 0.120 in., k_h = 0.0035 ft.

Table 10. Summary of Test Results, Test Series 7*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C'_e
1	68.5	0.1160	0.077	0.133	3.350	3.228
2	68.5	0.1605	0.107	0.215	3.348	3.240
3	69.0	0.2202	0.147	0.345	3.333	3.271
4	69.0	0.2885	0.192	0.516	3.329	3.270
5	69.0	0.3515	0.234	0.699	3.354	3.305
6	69.0	0.4373	0.292	0.972	3.360	3.329
7	69.0	0.5115	0.341	1.235	3.375	3.341
8	69.0	0.6020	0.401	1.587	3.397	3.372
9	69.5	0.6823	0.455	1.926	3.417	3.397
10	69.5	0.7600	0.507	2.284	3.447	3.426
11	70.0	0.8508	0.567	2.726	3.473	3.454
12	70.0	0.9362	0.624	3.170	3.500	3.484
13	70.0	1.0530	0.702	3.825	3.540	3.524
14	70.0	1.1232	0.749	4.248	3.568	3.555
15	69.0	0.0885	0.059	0.0879	3.340	3.149
16	69.0	0.0603	0.040	0.0499	3.367	3.158
17	66.5	0.0587	0.039	0.0484	3.406	3.141
18	66.5	0.0710	0.047	0.0643	3.403	3.200
19	66.5	0.0770	0.051	0.0721	3.367	3.188
20	67.0	0.0928	0.062	0.0950	3.355	3.197
21	67.5	0.1090	0.073	0.118	3.285	3.154
22	67.5	0.1510	0.107	0.193	3.291	3.199
23	67.5	0.2400	0.160	0.388	3.302	3.241
24	68.0	0.4673	0.312	1.072	3.357	3.328
25	68.0	0.8132	0.542	2.539	3.462	3.444
26	68.0	0.9838	0.656	3.431	3.516	3.498
27	68.0	1.1242	0.749	4.252	3.567	3.554
28	68.0	0.8967	0.598	2.961	3.487	3.468
29	68.0	0.5660	0.370	1.441	3.384	3.357
30	68.5	0.3907	0.260	0.813	3.330	3.289
31	68.5	0.2993	0.200	0.544	3.321	3.276
32	68.5	0.1748	0.117	0.242	3.305	3.216
33	68.5	0.2617	0.174	0.443	3.312	3.251
34	68.5	0.3913	0.261	0.819	3.345	3.311
35	68.0	0.1100	0.073	0.121	3.314	3.183
36	68.5	0.1865	0.124	0.265	3.293	3.204
37	68.5	0.2652	0.177	0.452	3.308	3.257
38	69.0	0.3600	0.240	0.720	3.332	3.291

*$t = 0.096$ in., $k_h = 0.0030$ ft.

Table 11. Summary of Test Results, Test Series 8*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
1	69.5	0.0712	0.047	0.0638	3.363	3.132
2	70.0	0.0840	0.056	0.0818	3.367	3.159
3	70.0	0.1085	0.072	0.120	3.345	3.189
4	70.0	0.1423	0.095	0.179	3.338	3.218
5	70.0	0.1850	0.123	0.263	3.307	3.217
6	70.0	0.2867	0.191	0.511	3.325	3.266
7	70.5	0.3873	0.258	0.804	3.335	3.291
8	70.5	0.4815	0.321	1.121	3.356	3.320
9	70.5	0.5750	0.383	1.476	3.385	3.354
10	70.5	0.6615	0.441	1.836	3.413	3.386
11	70.5	0.7710	0.514	2.334	3.447	3.424
12	70.5	0.8803	0.587	2.878	3.485	3.464
13	70.5	0.9895	0.660	3.468	3.523	3.505
14	70.0	1.0850	0.723	4.017	3.554	3.537
15	69.5	0.1865	0.124	0.265	3.293	3.204
16	69.5	0.4398	0.293	0.975	3.341	3.301
17	69.5	0.6223	0.415	1.665	3.392	3.364
18	69.5	0.8185	0.546	2.556	3.452	3.430
19	69.5	1.0335	0.689	3.710	3.531	3.513
20	69.5	1.1363	0.758	4.325	3.570	3.554
21	69.5	0.9232	0.615	3.101	3.496	3.459
22	69.5	0.7153	0.477	2.070	3.422	3.397
23	69.5	0.5248	0.350	1.279	3.365	3.331
24	69.0	0.2820	0.188	0.508	3.338	3.275
25	69.5	0.3415	0.228	0.664	3.327	3.278
26	69.5	0.2398	0.160	0.389	3.314	3.244
27	69.5	0.1942	0.129	0.283	3.308	3.219
28	70.0	0.4468	0.298	0.999	3.345	3.306
29	70.0	0.8518	0.568	2.724	3.464	3.443

*t = 0.072 in., k_h = 0.0035 ft.

Table 12. Summary of Test Results, Test Series 9*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
1	70.0	0.0830	0.055	0.0793	3.318	3.116
2	70.0	0.1042	0.069	0.113	3.350	3.184
3	71.0	0.1432	0.095	0.180	3.329	3.210
4	71.0	0.1998	0.133	0.296	3.310	3.223
5	71.0	0.2988	0.199	0.542	3.319	3.261
6	71.0	0.3880	0.259	0.807	3.340	3.296
7	71.0	0.4910	0.327	1.156	3.358	3.323
8	70.0	0.3522	0.235	0.698	3.338	3.289
9	70.0	0.4595	0.306	1.045	3.353	3.316
10	70.0	0.5430	0.362	1.349	3.372	3.339
11	70.0	0.6550	0.437	1.809	3.412	3.384
12	70.0	0.7818	0.521	2.382	3.447	3.424
13	70.0	0.8995	0.600	2.972	3.484	3.464
14	69.5	1.0212	0.681	3.641	3.528	3.510
15	69.5	1.1275	0.752	4.284	3.578	3.561
16	69.5	1.0682	0.712	3.924	3.554	3.537
17	69.5	0.9450	0.630	3.220	3.505	3.486
18	69.5	0.8402	0.560	2.670	3.466	3.445
19	69.5	0.7175	0.478	2.085	3.431	3.406
20	69.5	0.6018	0.401	1.585	3.395	3.365
21	69.5	0.3155	0.210	0.590	3.327	3.272
22	69.5	0.2712	0.181	0.469	3.317	3.255
23	69.5	0.2250	0.150	0.354	3.318	3.240
24	69.0	0.1828	0.122	0.259	3.316	3.224
25	69.0	0.1290	0.086	0.154	3.322	3.188
26	69.0	0.1010	0.067	0.108	3.353	3.190
27	69.0	0.0720	0.048	0.0647	3.350	3.116
28	69.0	0.0805	0.054	0.0755	3.304	3.107

*t = 0.048 in., k_h = 0.0035 ft.

Table 13. Summary of Test Results, Test Series 10*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
1	69.0	0.0672	0.045	0.0570	3.282	3.103
2	69.5	0.0788	0.053	0.0723	3.270	3.115
3	69.5	0.0918	0.061	0.0917	3.296	3.167
4	70.0	0.1155	0.077	0.129	3.291	3.189
5	70.0	0.1590	0.106	0.208	3.283	3.207
6	70.0	0.1992	0.133	0.292	3.288	3.228
7	70.0	0.2735	0.182	0.473	3.305	3.259
8	70.5	0.3570	0.238	0.708	3.317	3.282
9	70.5	0.4710	0.314	1.082	3.349	3.322
10	70.5	0.5740	0.383	1.435	3.377	3.355
11	71.0	0.6800	0.453	0.561	3.414	3.395
12	71.0	0.7917	0.528	0.704	3.462	3.445
13	71.0	0.9073	0.605	0.864	3.490	3.475
14	71.0	1.0202	0.680	1.030	3.534	3.521
15	71.0	1.1363	0.758	1.211	3.581	3.570
16	71.0	1.0803	0.720	1.123	3.564	3.551
17	71.0	0.9610	0.641	0.942	3.516	3.502
18	71.0	0.8485	0.566	0.782	3.480	3.465
19	71.0	0.7910	0.527	0.704	3.461	3.445
20	71.0	0.7408	0.494	2.193	3.440	3.423
21	67.0	0.2408	0.161	0.389	3.289	3.238
22	67.5	0.4298	0.287	0.936	3.323	3.294
23	68.0	0.6142	0.409	1.632	3.391	3.370
24	68.0	0.8322	0.555	2.629	3.463	3.448
25	68.0	0.5110	0.341	1.224	3.351	3.327
26	68.0	0.4352	0.290	0.956	3.331	3.302
27	68.0	0.3115	0.208	0.573	3.298	3.258
28	68.0	0.2195	0.146	0.337	3.281	3.226
29	69.0	0.1430	0.095	0.176	3.259	3.177
30	69.0	0.0973	0.065	0.0979	3.225	3.105
31	69.0	0.1530	0.102	0.197	3.302	3.221
32	69.5	0.3713	0.248	0.751	3.319	3.287
33	69.5	0.7790	0.519	2.366	3.442	3.425
34	69.5	0.7192	0.479	2.091	3.428	3.411
35	70.0	0.2660	0.177	0.454	3.310	3.265
36	70.0	0.1970	0.131	0.288	3.290	3.228
37	70.0	0.1070	0.071	0.115	3.298	3.184
38	70.0	0.0910	0.061	0.0902	3.279	3.153

*$t = 0.023$ in., $k_h = 0.0025$ ft.

Table 14. Summary of Test Results, Test Series 11*

Run	Temperature (°F)	Head (h) (ft)	h/P	Discharge (Q) (cfs)	C	C_e'
1	66.0	0.1090	0.073	0.117	3.253	3.144
2	66.0	0.1485	0.099	0.187	3.273	3.189
3	66.0	0.1878	0.125	0.268	3.292	3.227
4	66.0	0.2377	0.159	0.382	3.295	3.244
5	66.5	0.3215	0.214	0.606	3.325	3.287
6	67.0	0.4458	0.297	0.996	3.346	3.318
7	67.0	0.5445	0.363	1.357	3.377	3.353
8	67.0	0.6500	0.433	1.782	3.401	3.381
9	67.0	0.7430	0.495	2.198	3.432	3.414
10	66.0	0.1220	0.081	0.142	3.323	3.225
11	66.5	0.2913	0.194	0.521	3.313	3.271
12	66.5	0.5168	0.345	1.245	3.351	3.327
13	66.5	0.6920	0.461	1.967	3.416	3.398
14	67.0	0.8480	0.565	2.705	3.463	3.448
15	67.0	0.9620	0.641	3.296	3.494	3.480
16	67.0	1.0452	0.697	3.796	3.533	3.521
17	67.0	1.1267	0.751	4.255	3.558	3.546
18	67.0	0.9990	0.666	3.512	3.517	3.504
19	67.0	0.8030	0.535	2.481	3.447	3.432
20	67.0	0.1760	0.117	0.243	3.294	3.224
21	67.0	0.3880	0.259	0.804	3.327	3.295
22	67.0	0.5967	0.398	1.558	3.381	3.360
23	67.0	0.8948	0.597	2.940	3.474	3.459
24	67.0	1.0893	0.726	4.035	3.549	3.537
25	67.5	1.1380	0.759	4.348	3.581	3.569
26	67.5	0.9463	0.631	3.222	3.500	3.486
27	67.5	0.2300	0.153	0.364	3.297	3.243
28	67.5	0.4205	0.280	0.911	3.342	3.313
29	67.5	0.5030	0.335	1.200	3.364	3.339
30	68.0	0.3465	0.231	0.677	3.321	3.284
31	68.0	0.1420	0.095	0.176	3.289	3.205

*t = knife edged, k_h = 0.0025 ft.

F I G U R E S

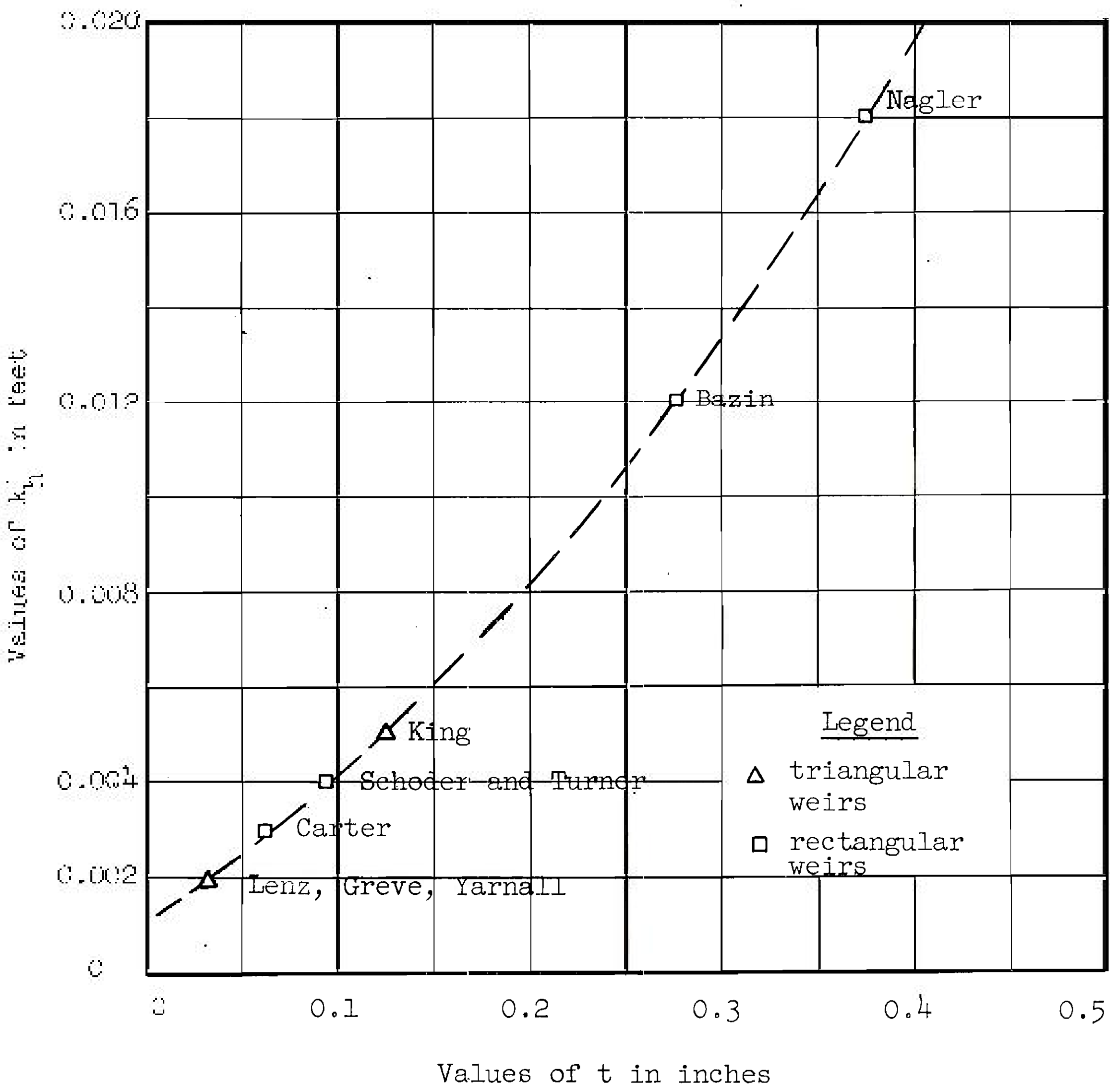

Fig. 1. Relation between k_h and t (Shen)

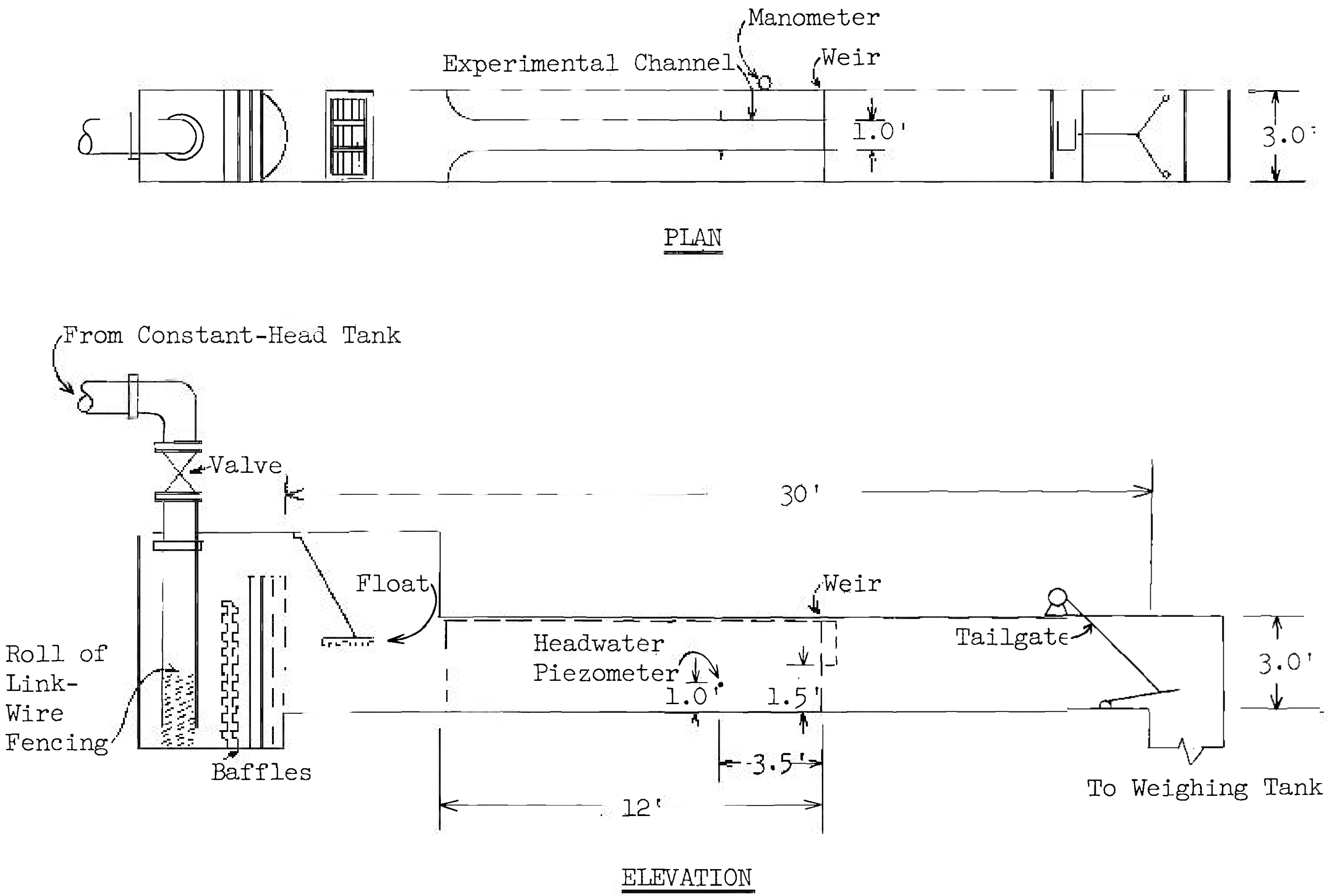

Fig. 2. General Arrangement of Experimental Equipment

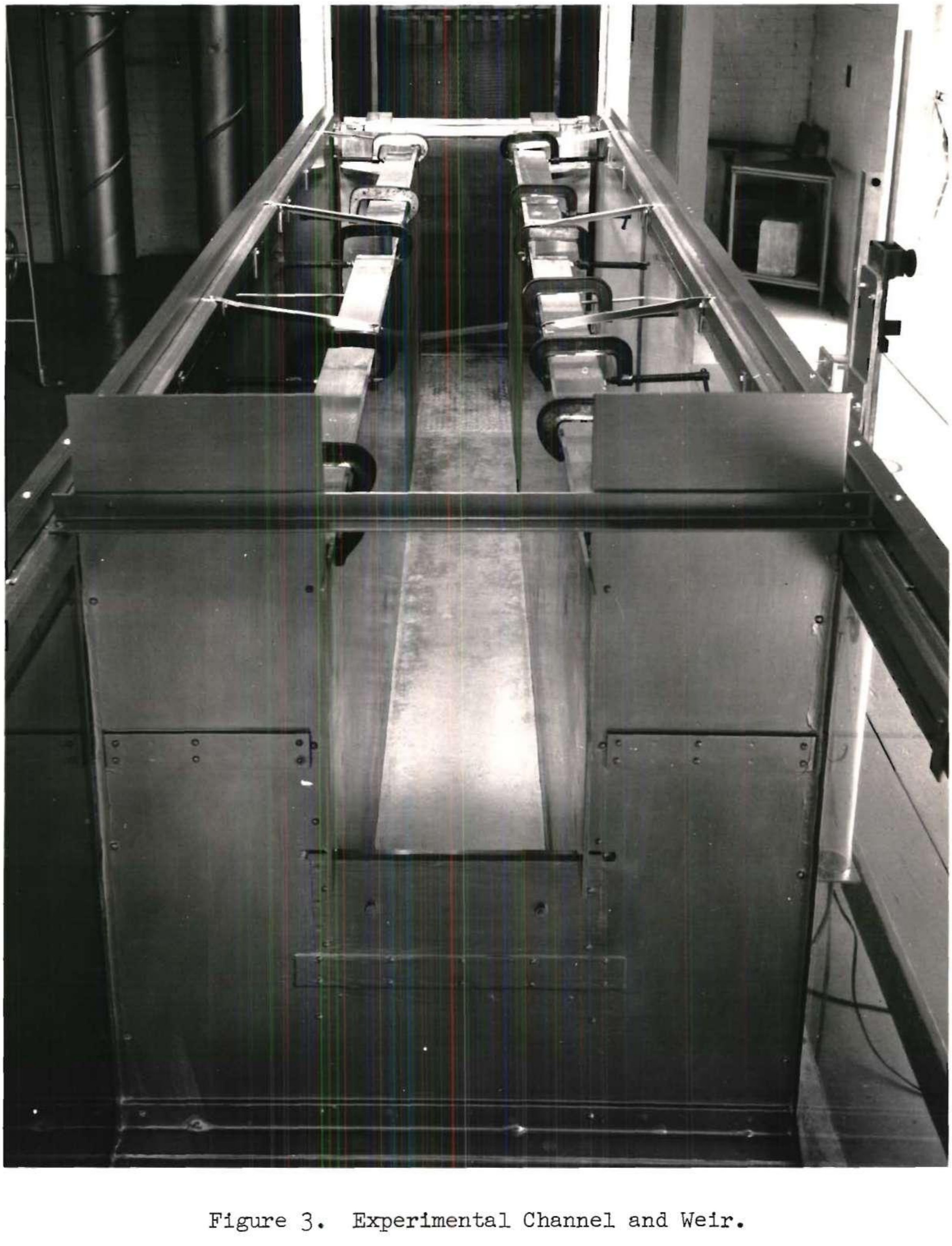

Figure 3. Experimental Channel and Weir.

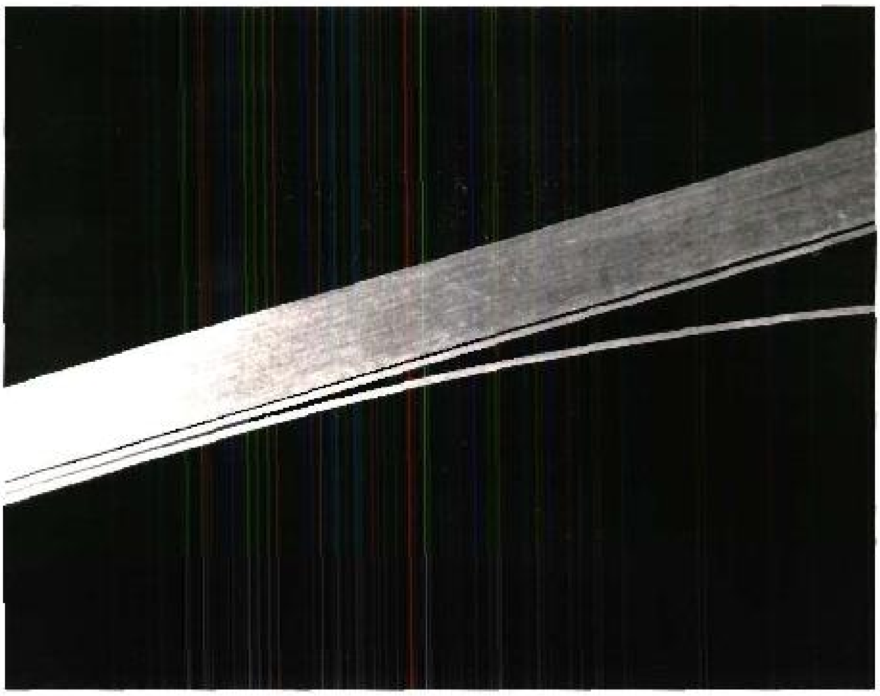

Figure 4. Closeup of Weir-Crest.

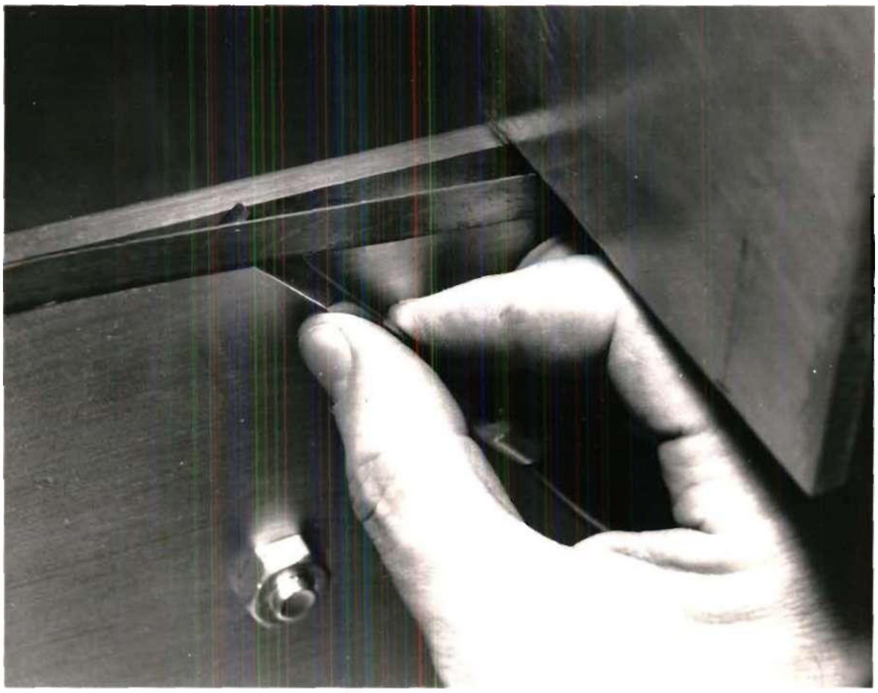

Figure 5. Stripping Laminae to Change Weir-Crest Thickness.

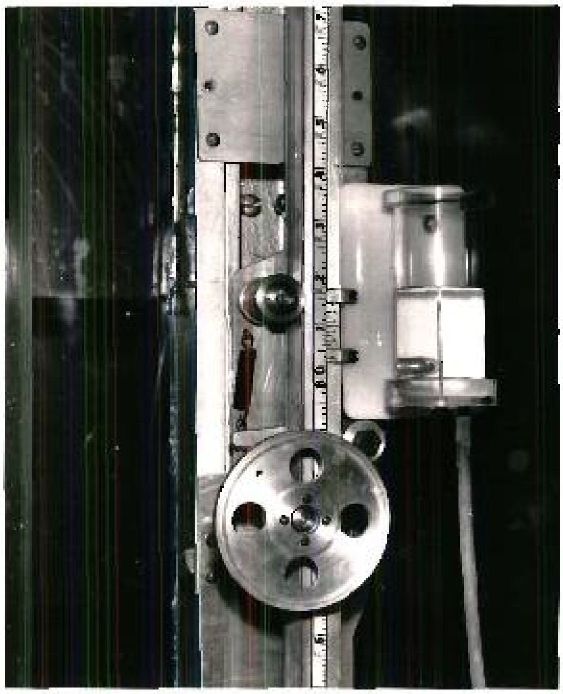

Figure 6. Manometer Stilling Well and Needle.

Figure 7. Experimental Flume and Weighing Tank.

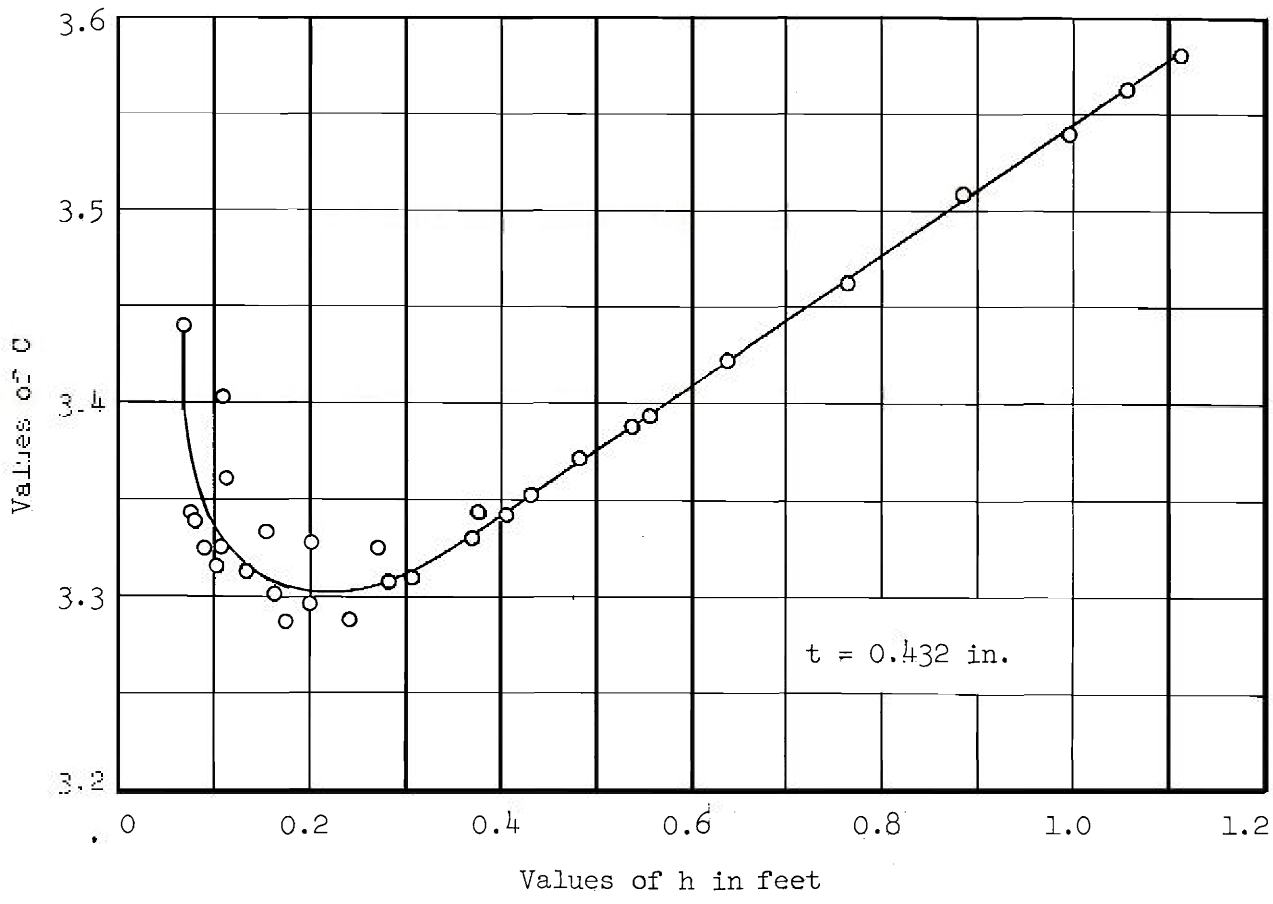

Fig. 8. C as a Function of h, Test 1

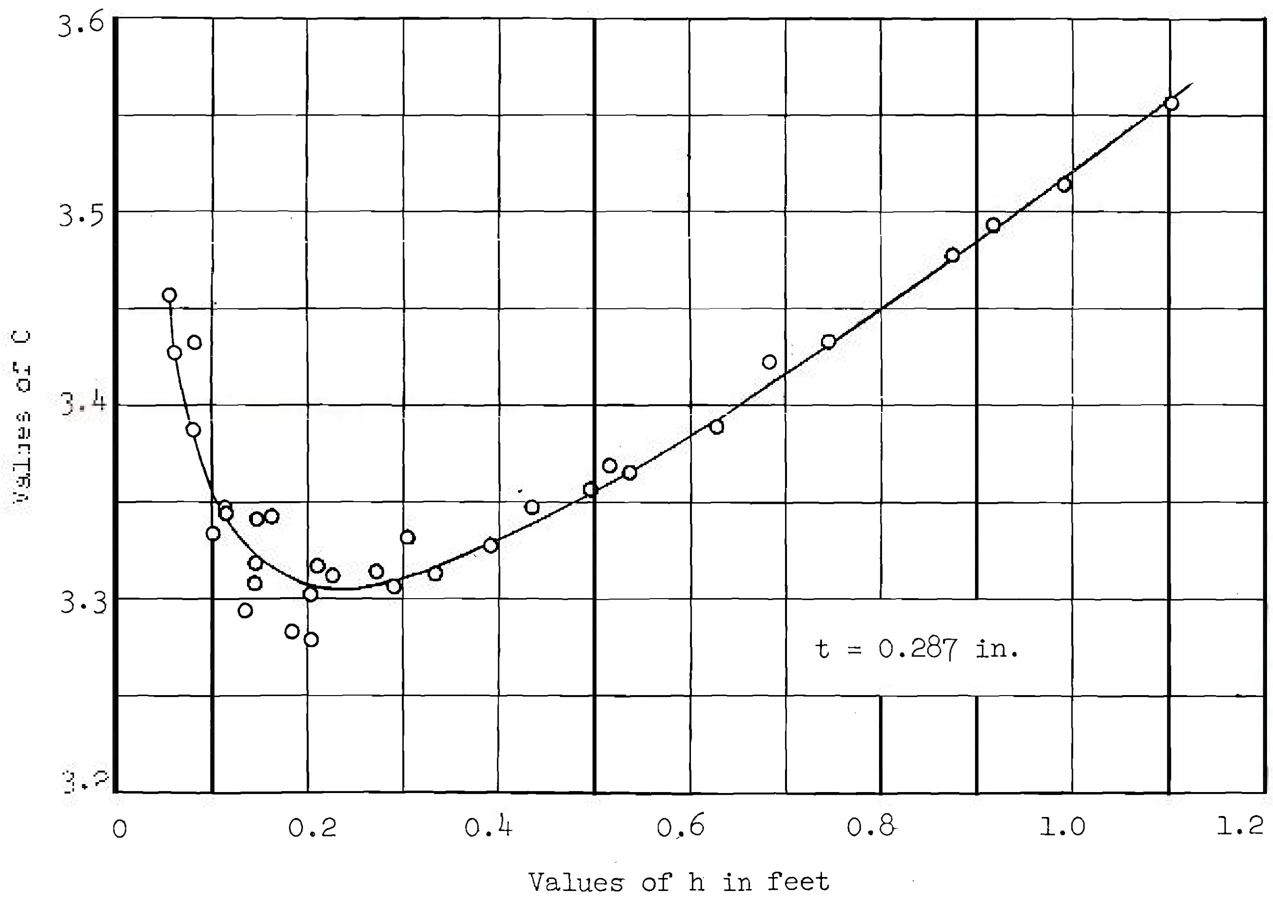

Fig. 9. C as a Function of h, Test 3

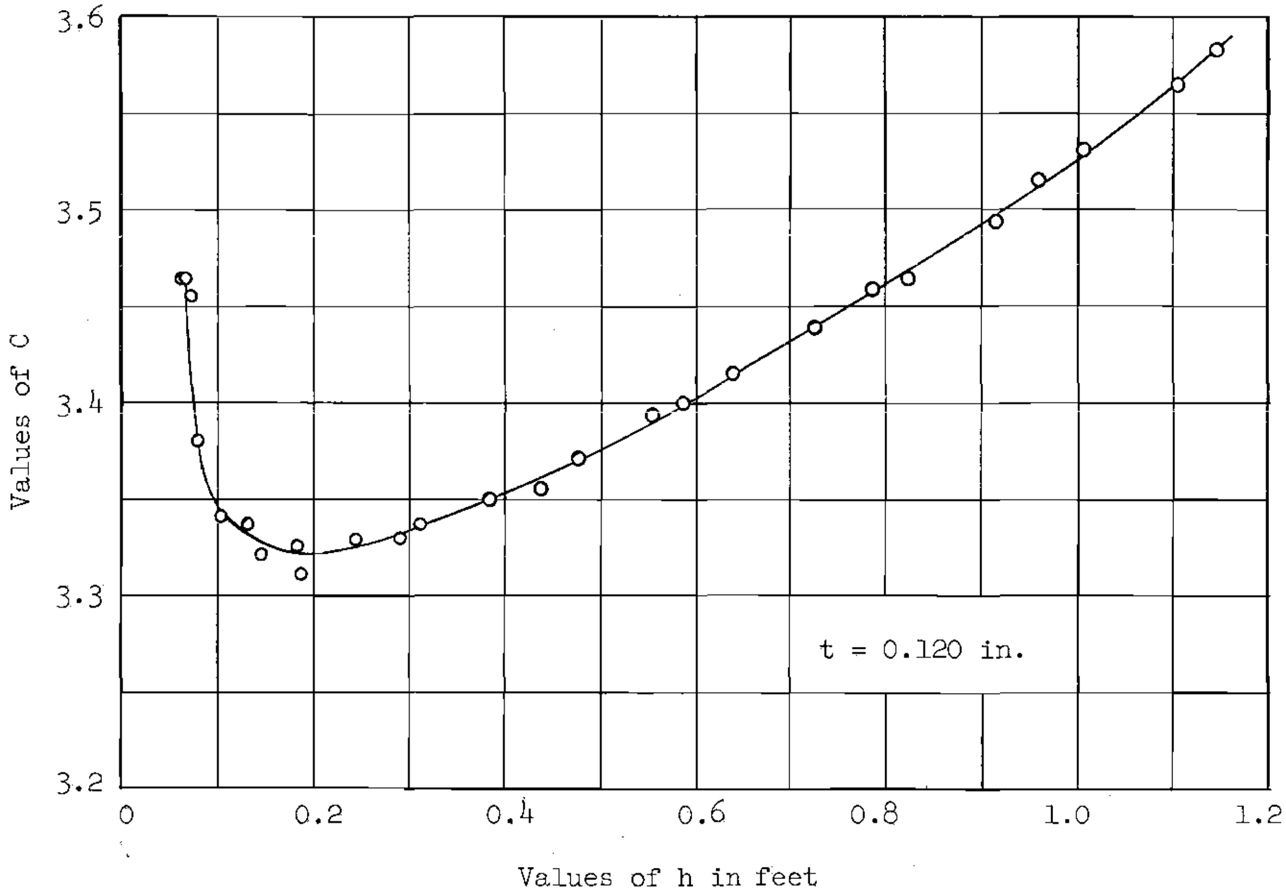

Fig. 10. C as a Function of h, Test 6

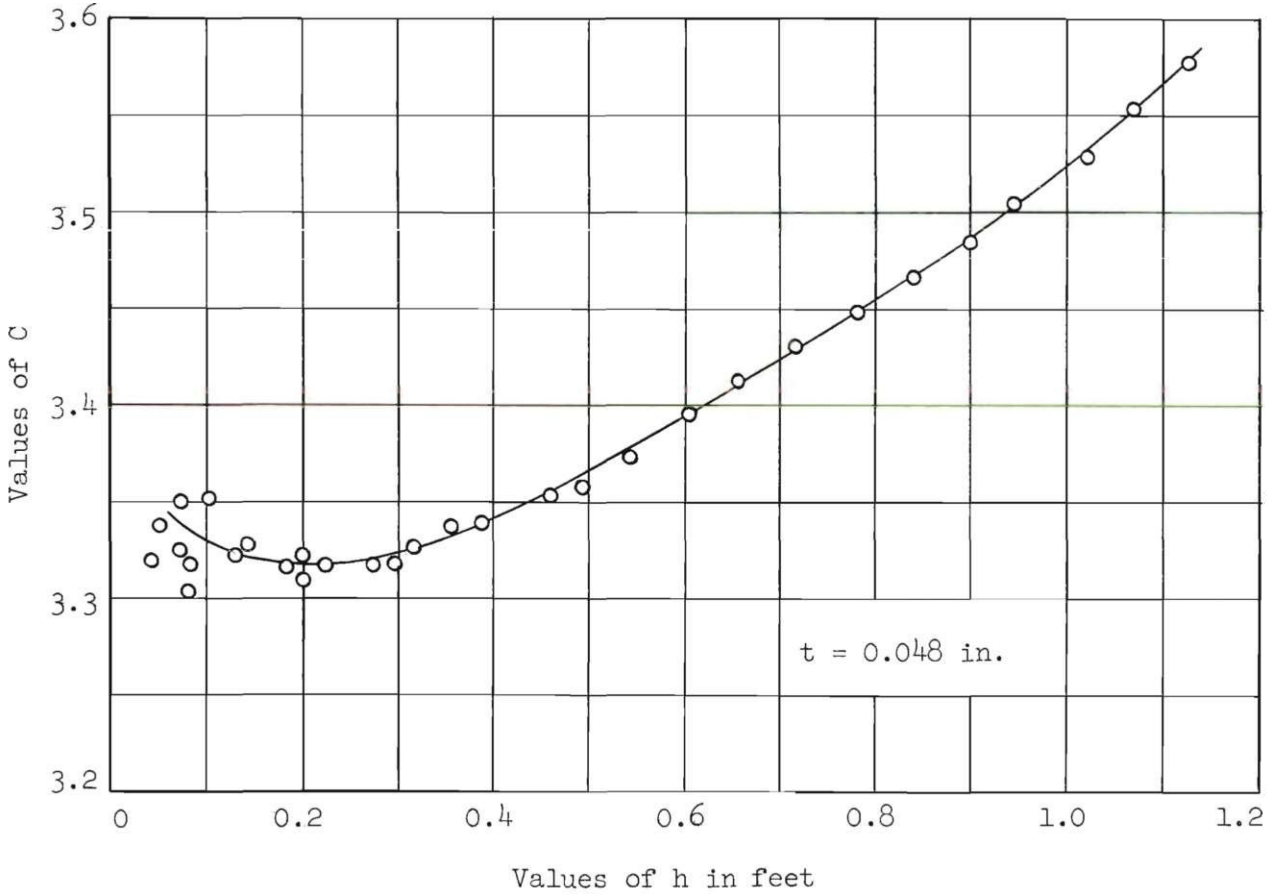

Fig. 11. C as a Function of h, Test 9

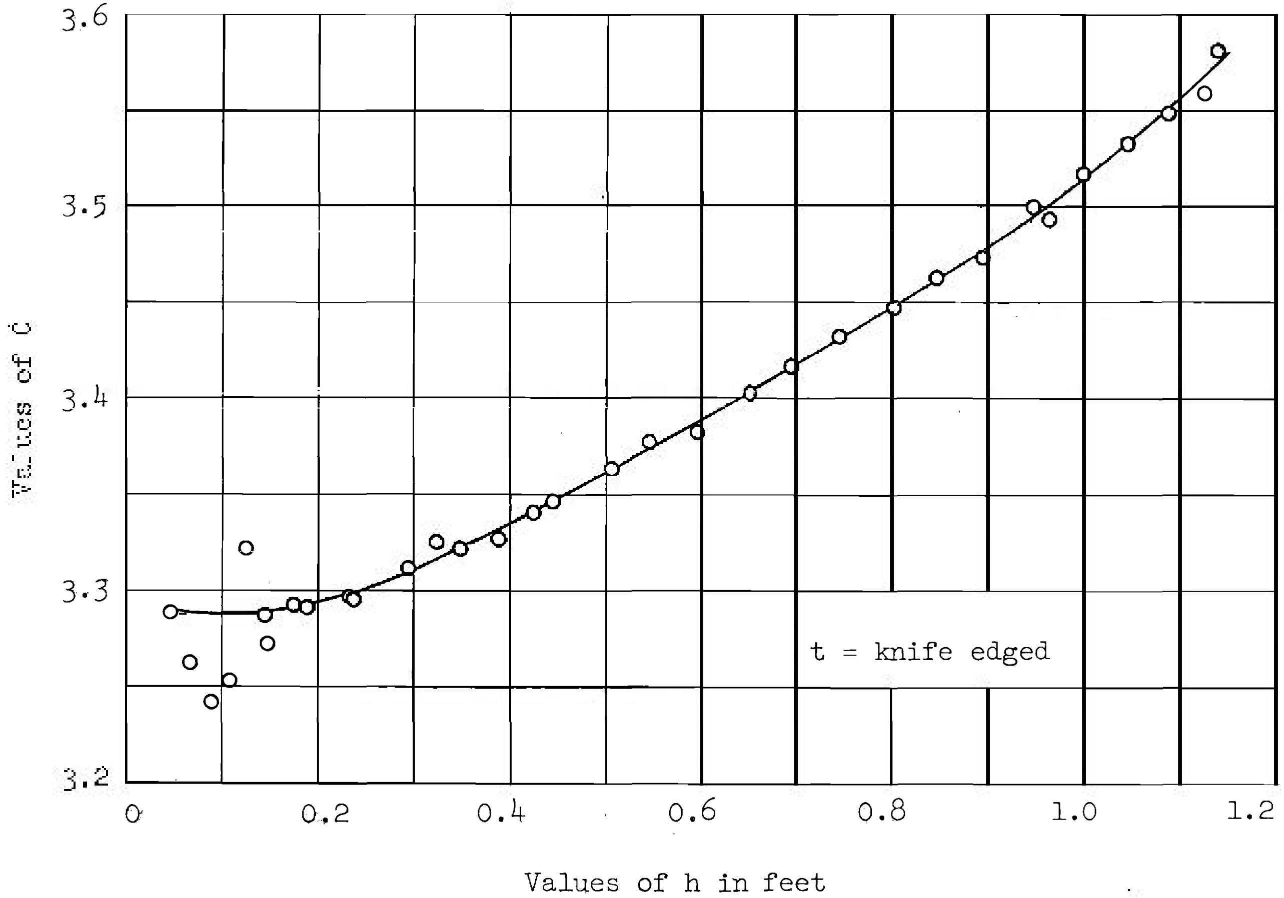

Fig. 12. C as a Function of h, Test 11

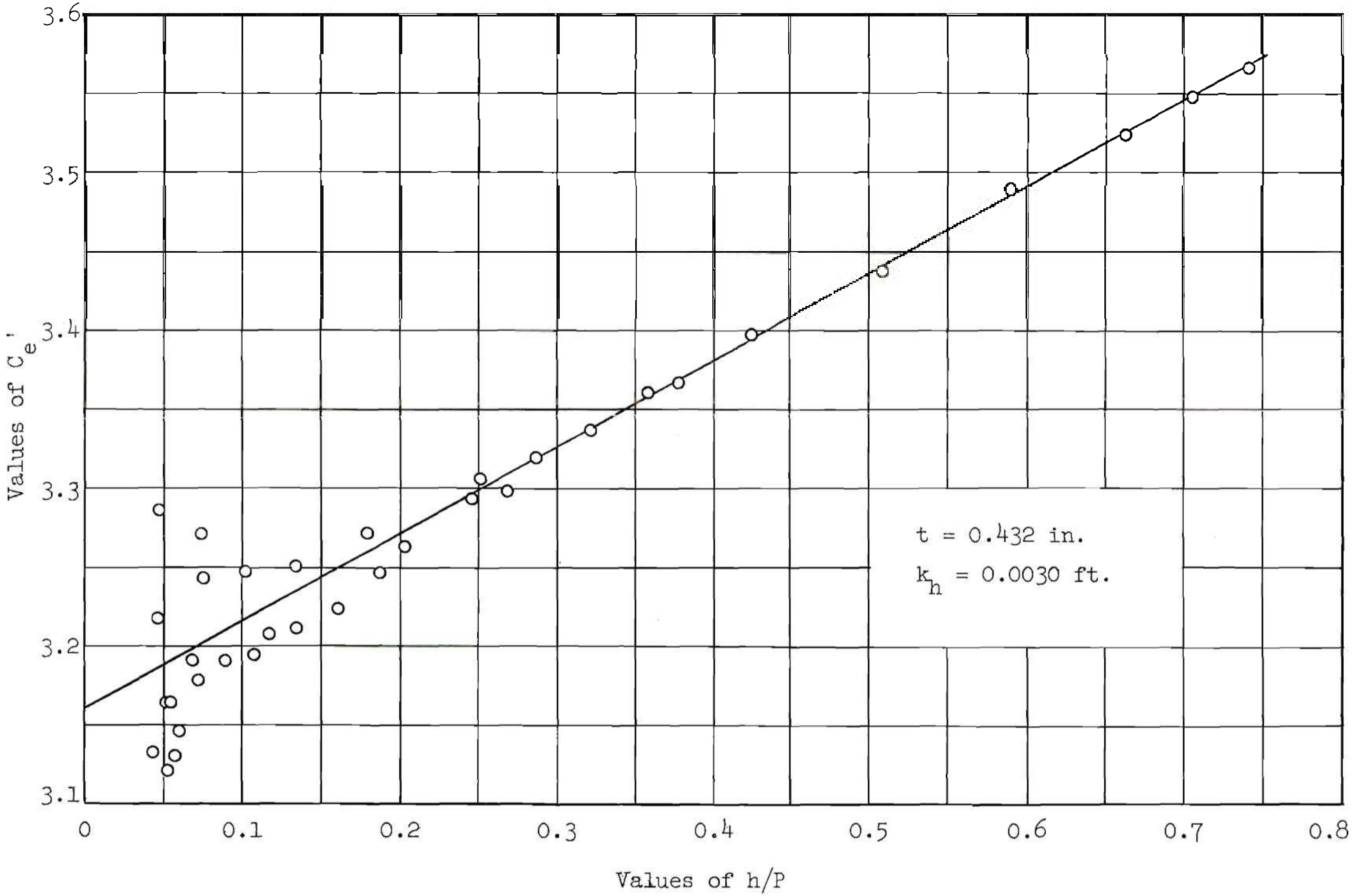

Fig. 13. C_e' as a Function of h/P, Test 1

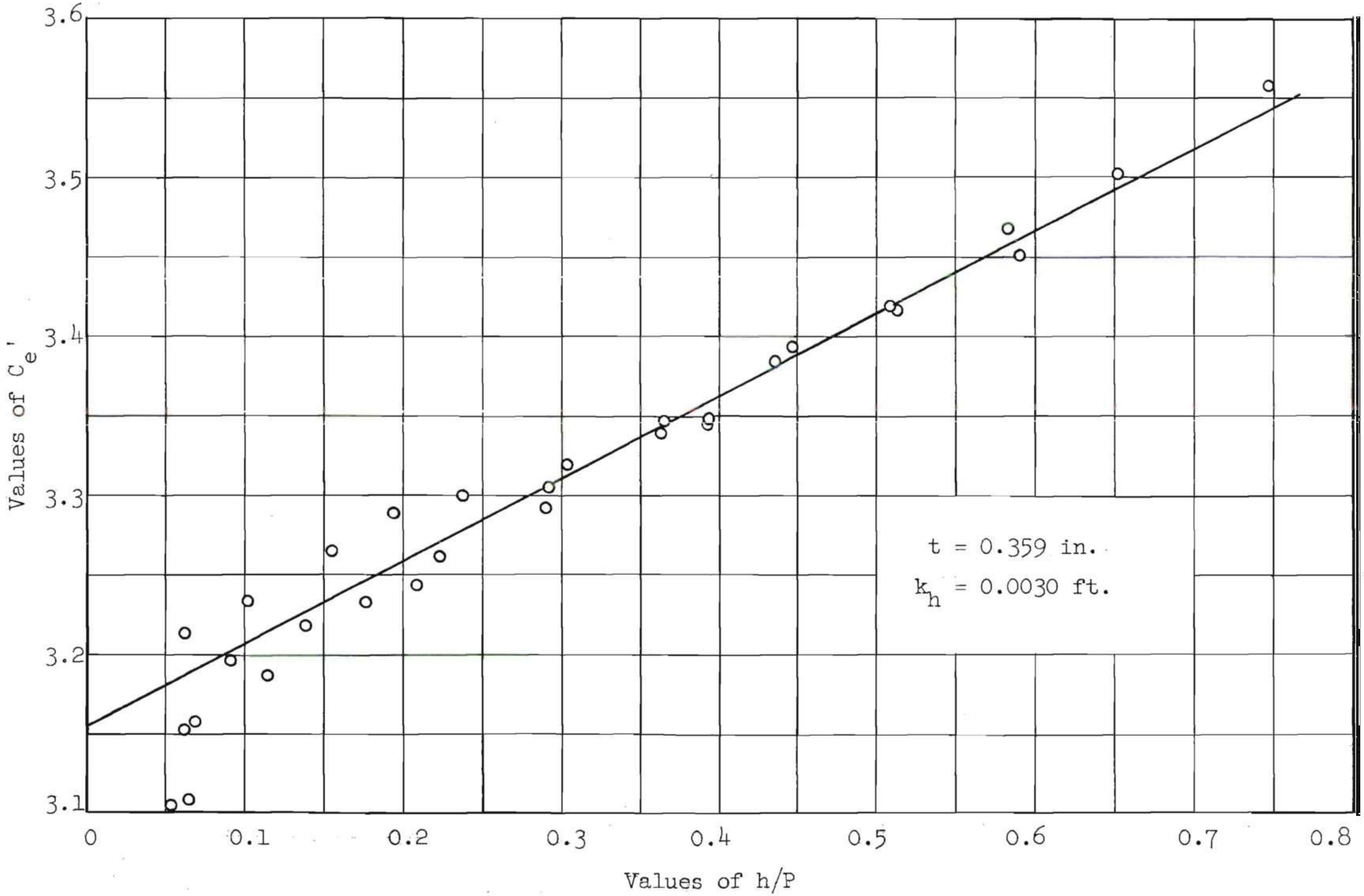

Fig. 14. $C_e{}'$ as a Function of h/P, Test 2

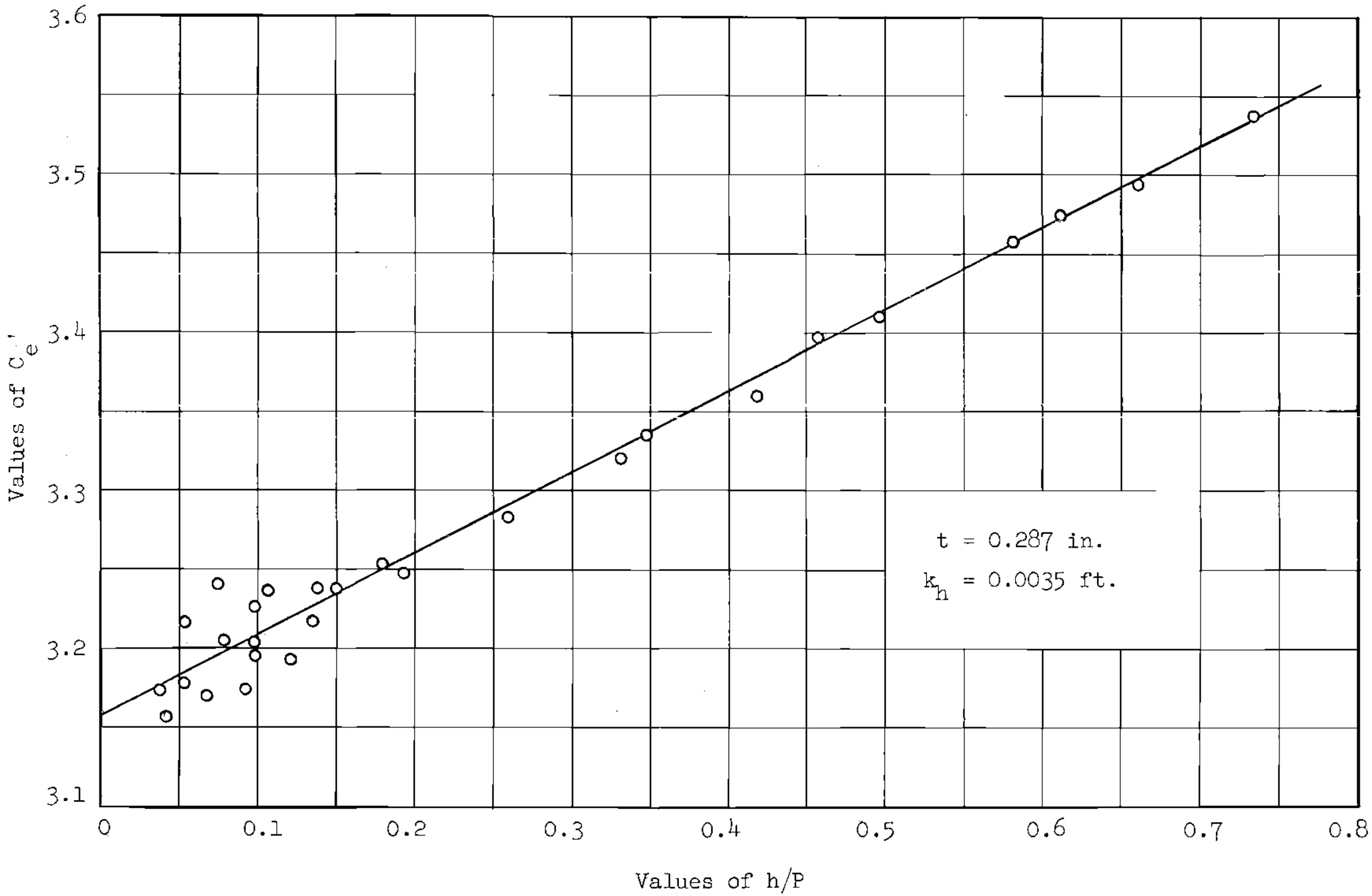

Fig. 15. C_e' as a Function of h/P, Test 3

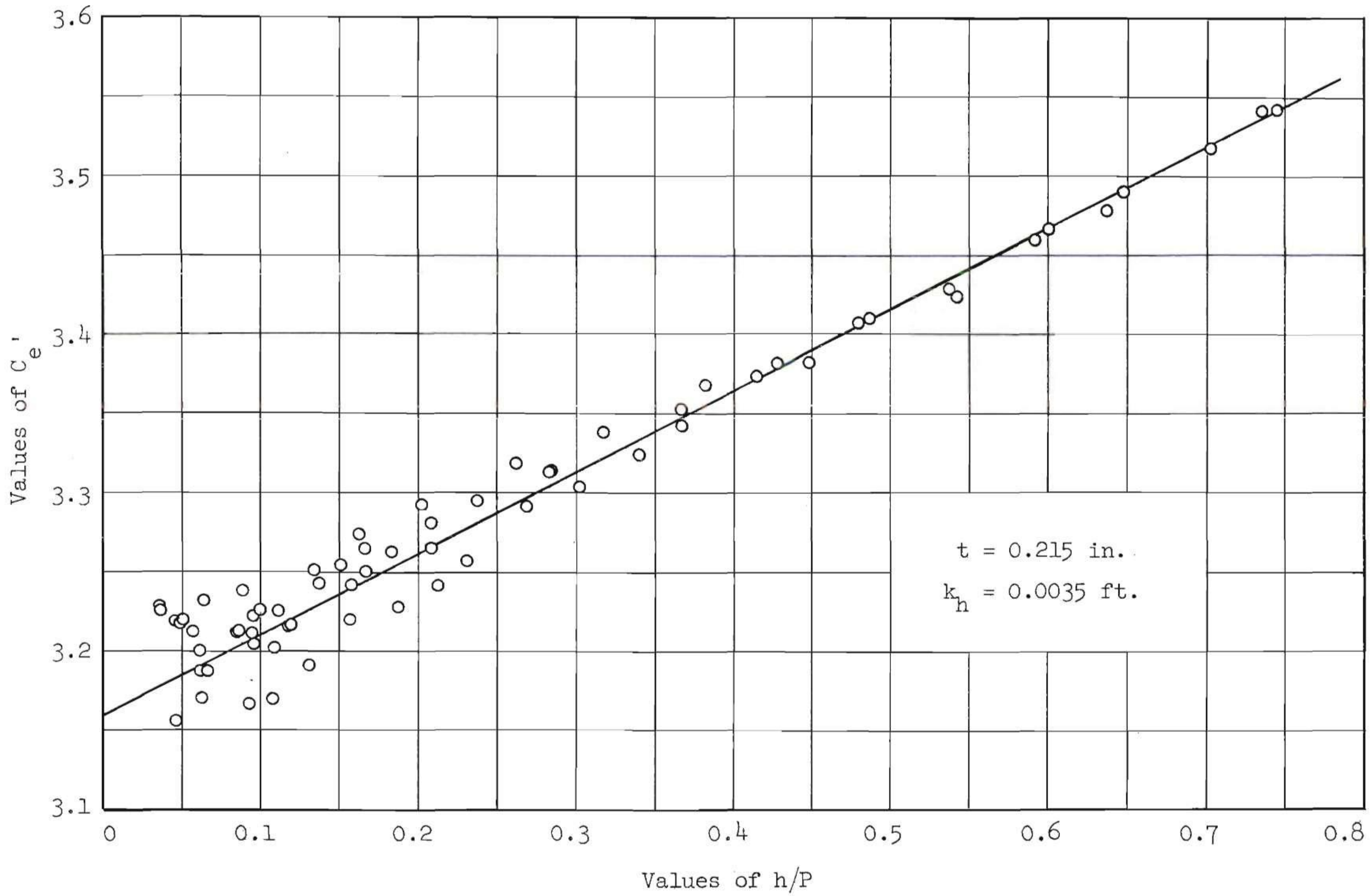

Fig. 16. C_e' as a Function of h/P, Test 4

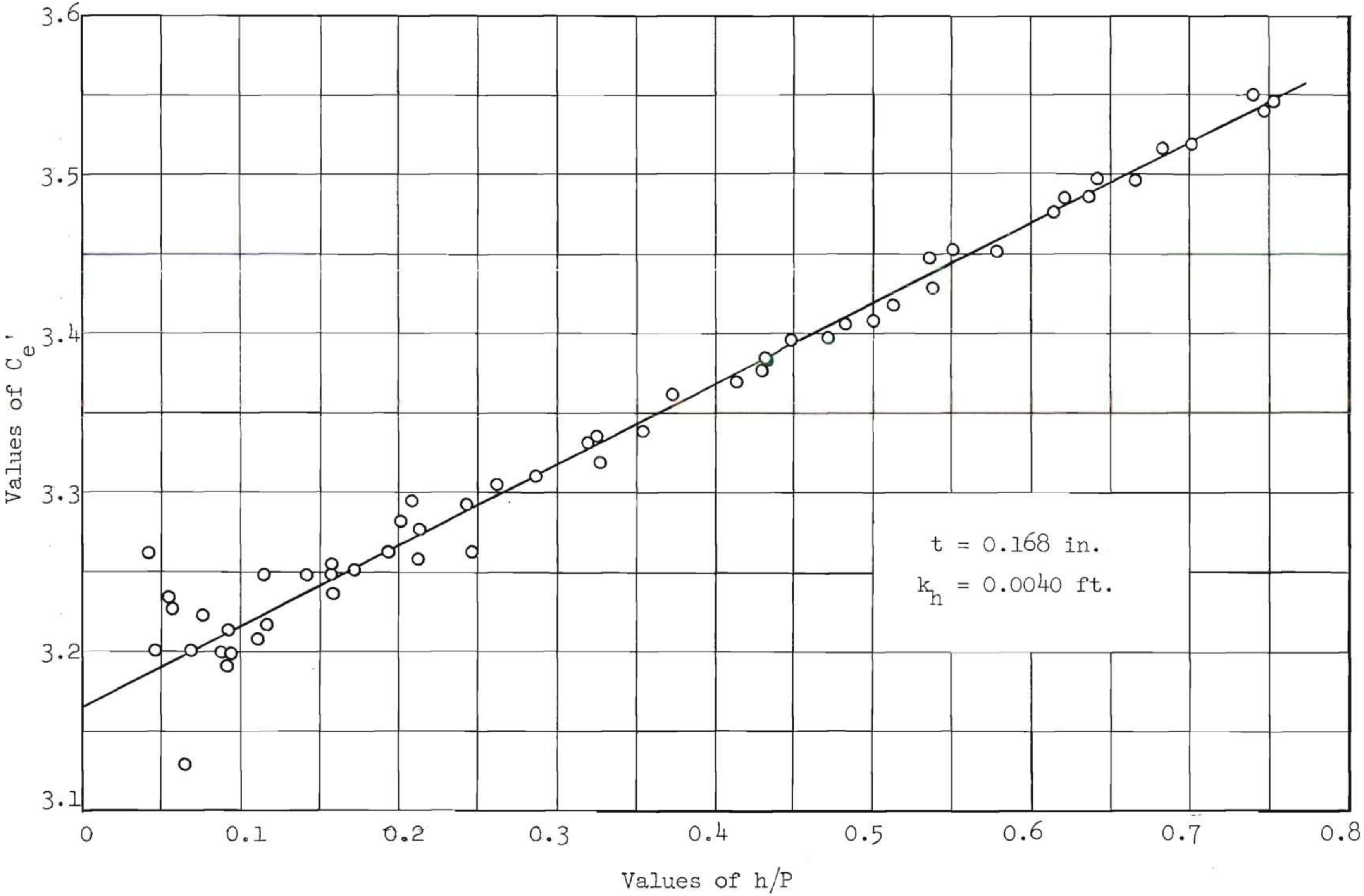

Fig. 17. C_e' as a Function of h/P, Test 5

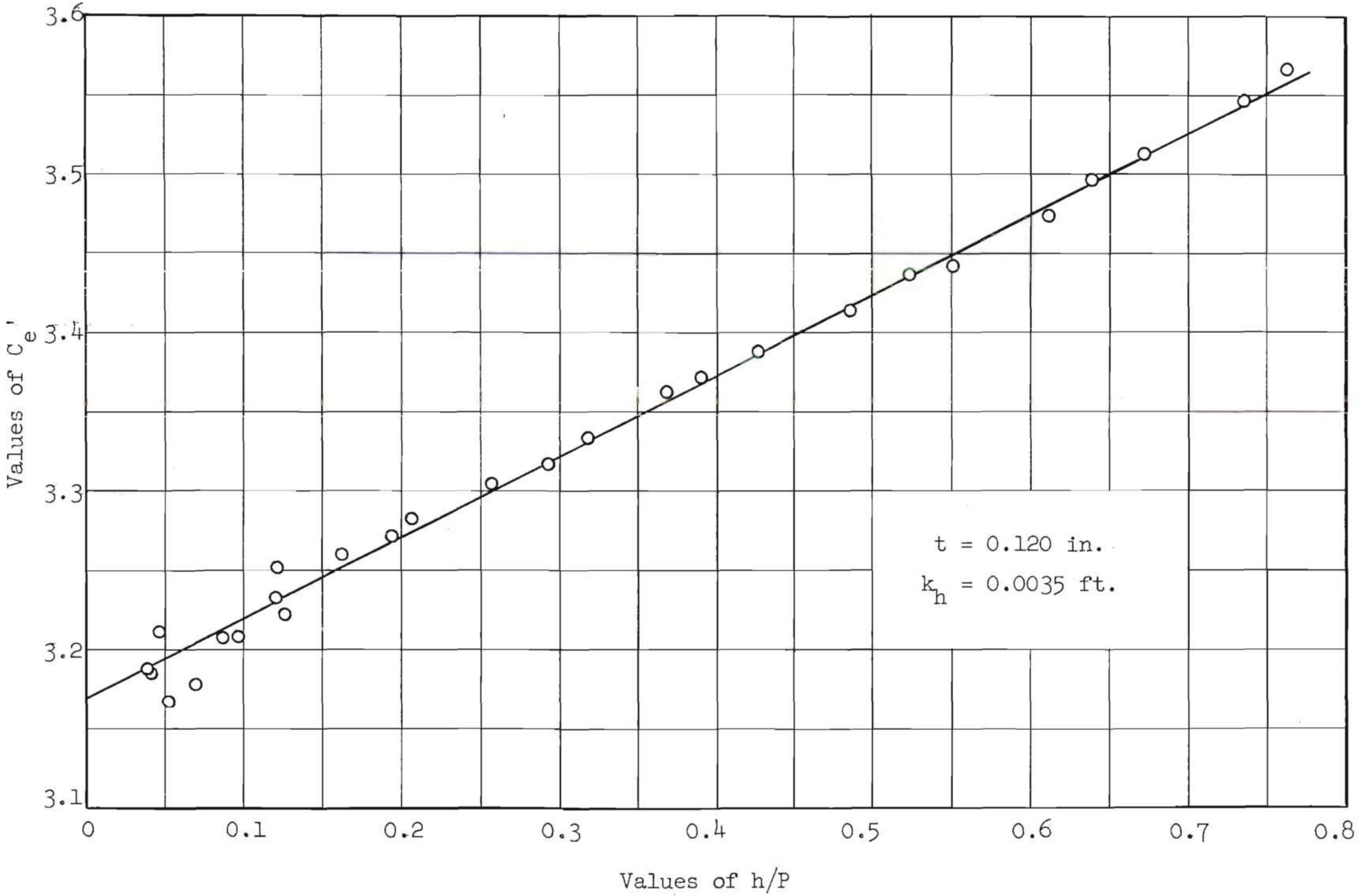

Fig. 18. C_e' as a Function of h/P, Test 6

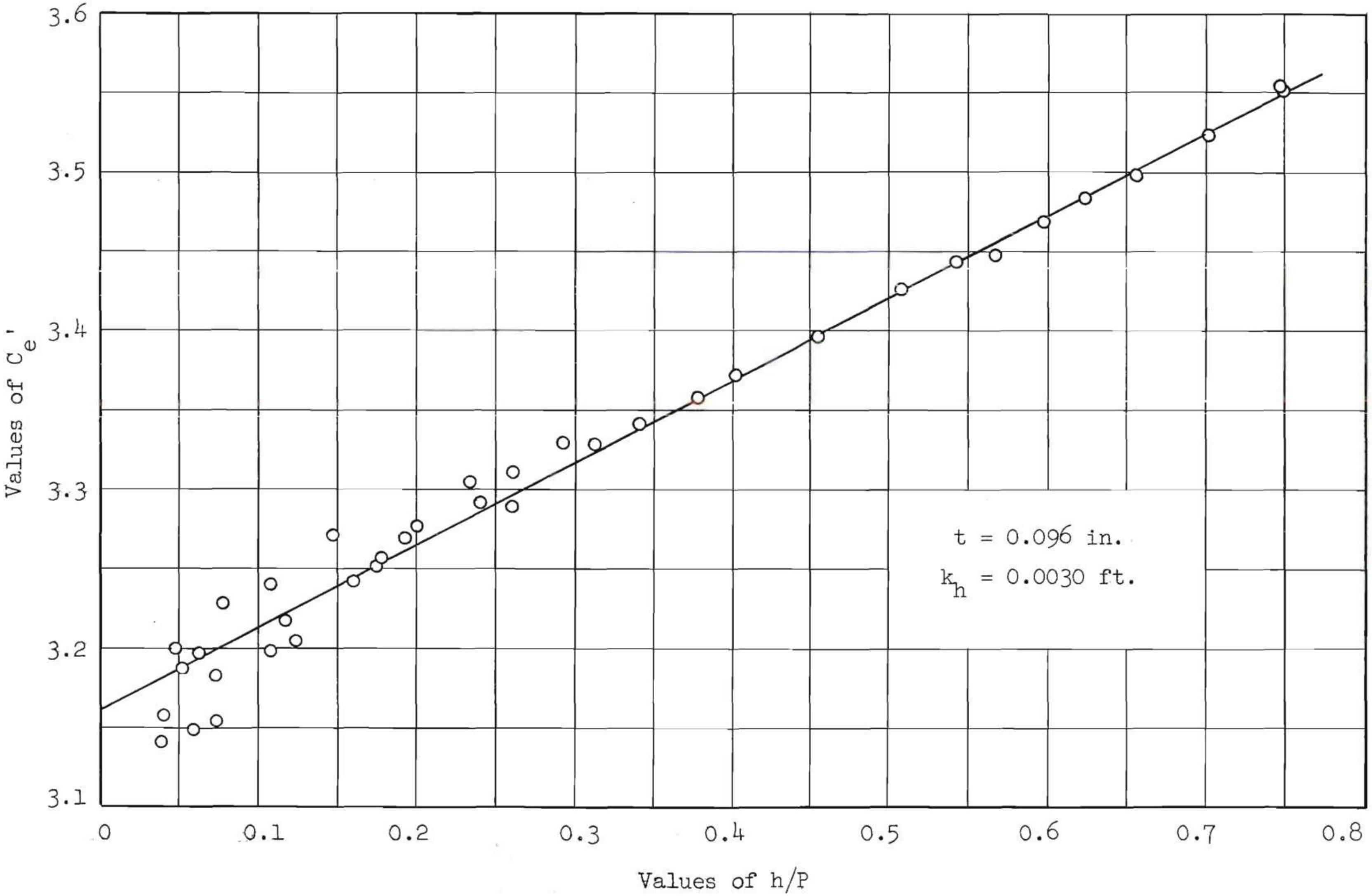

Fig. 19. C_e' as a Function of h/P, Test 7

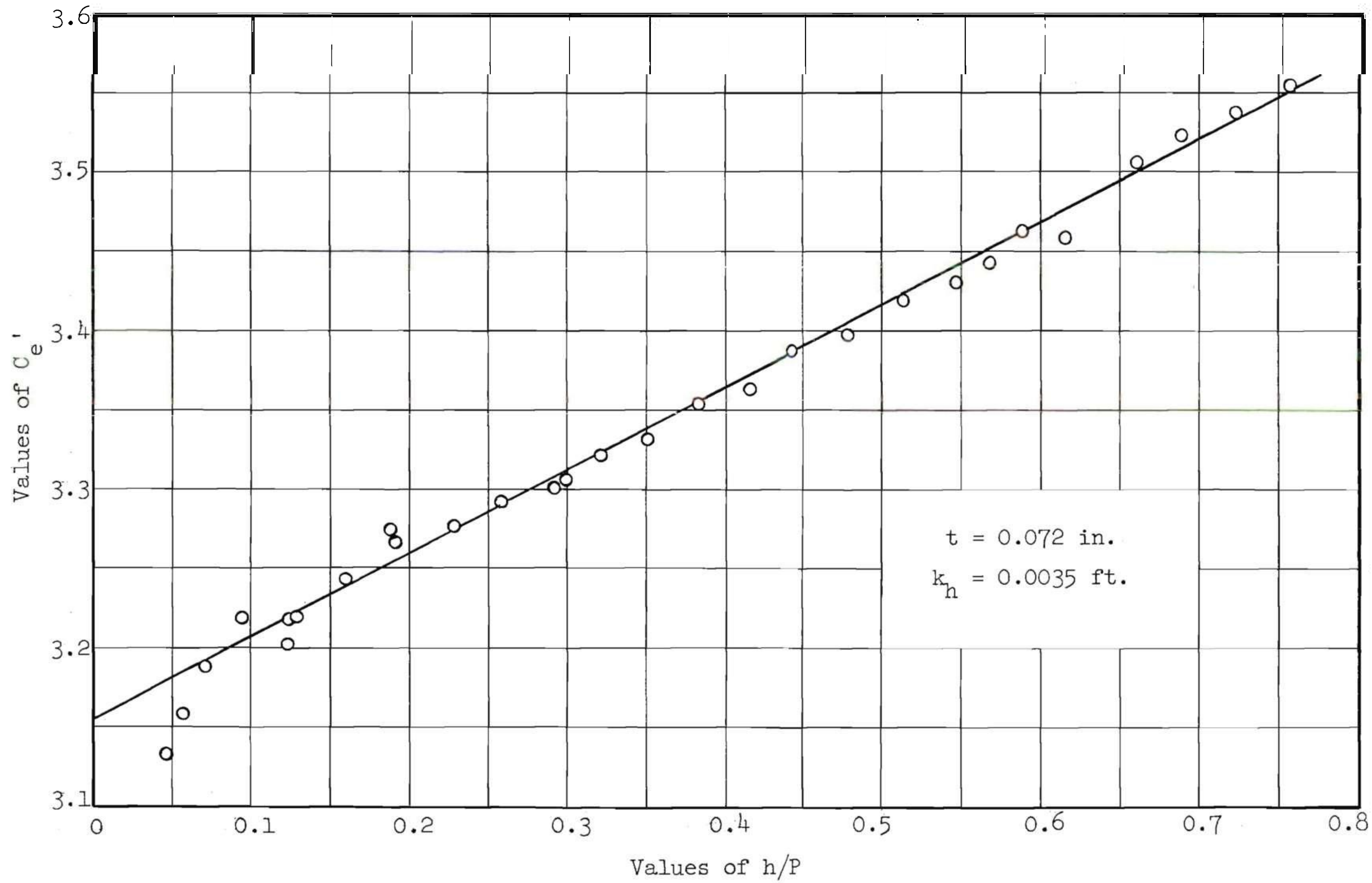

Fig. 20. C_e' as a Function of h/P, Test 8

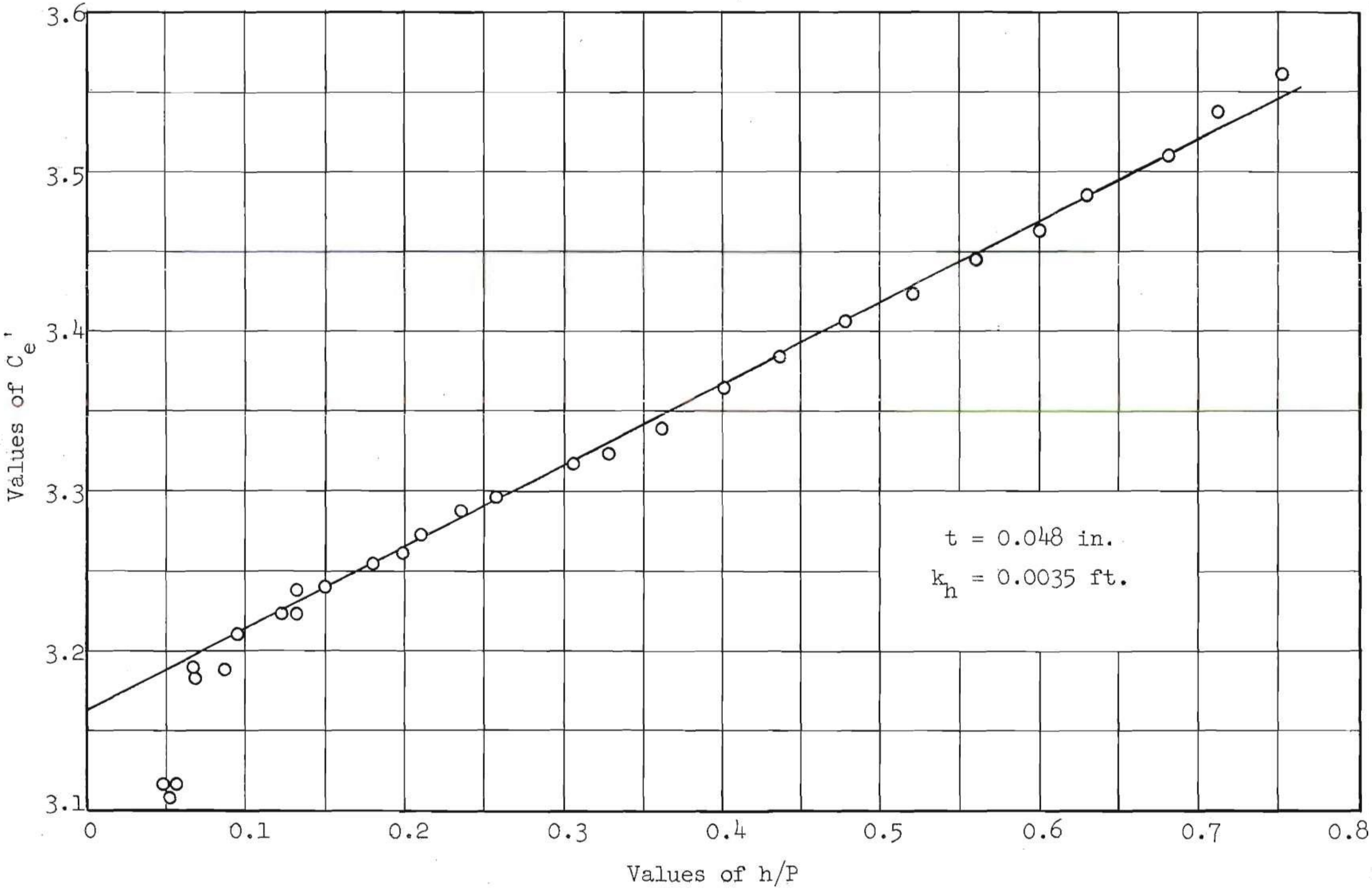

Fig. 21. C_e' as a Function of h/P, Test 9

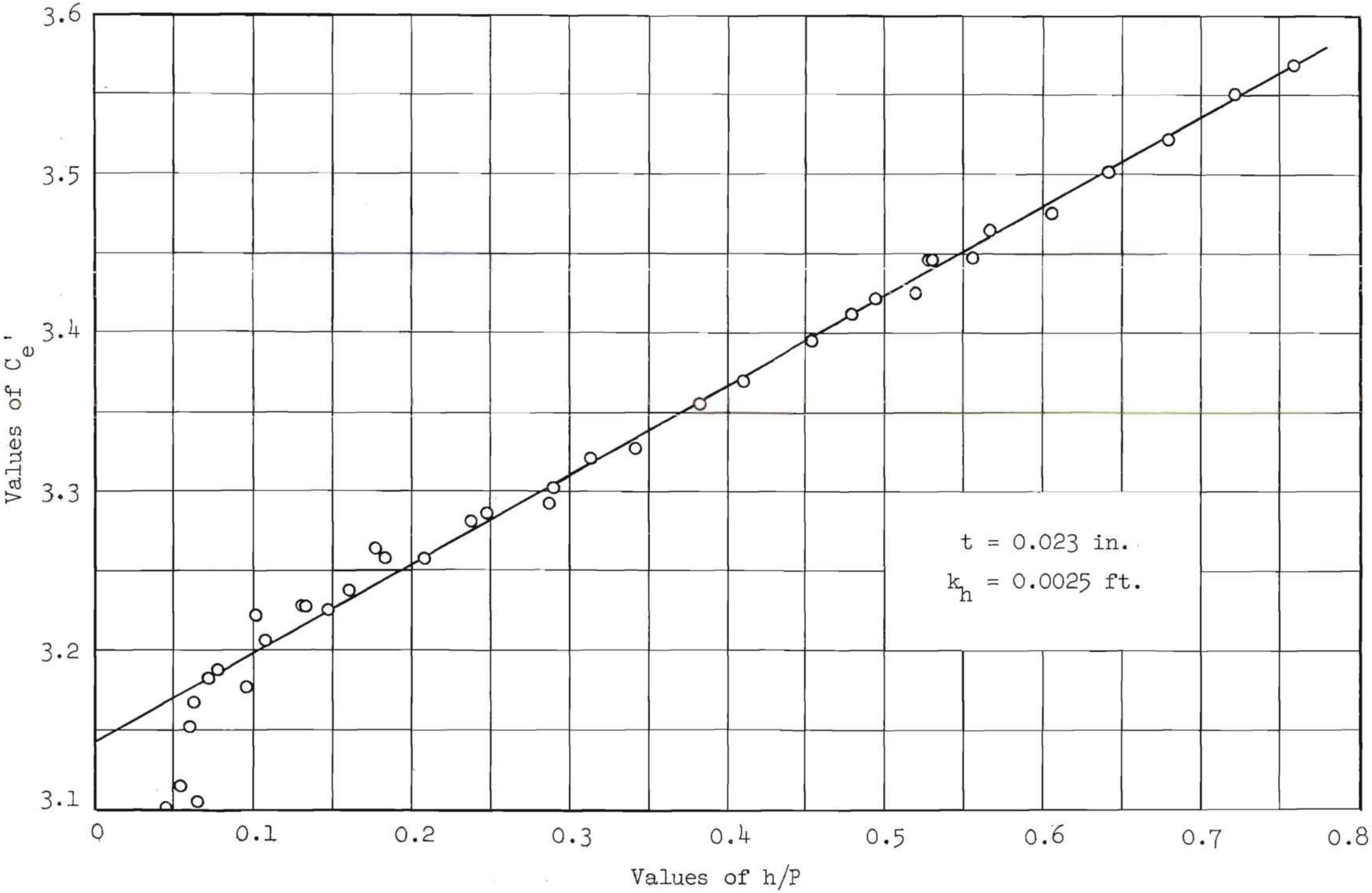

Fig. 22. C_e' as a Function of h/P, Test 10

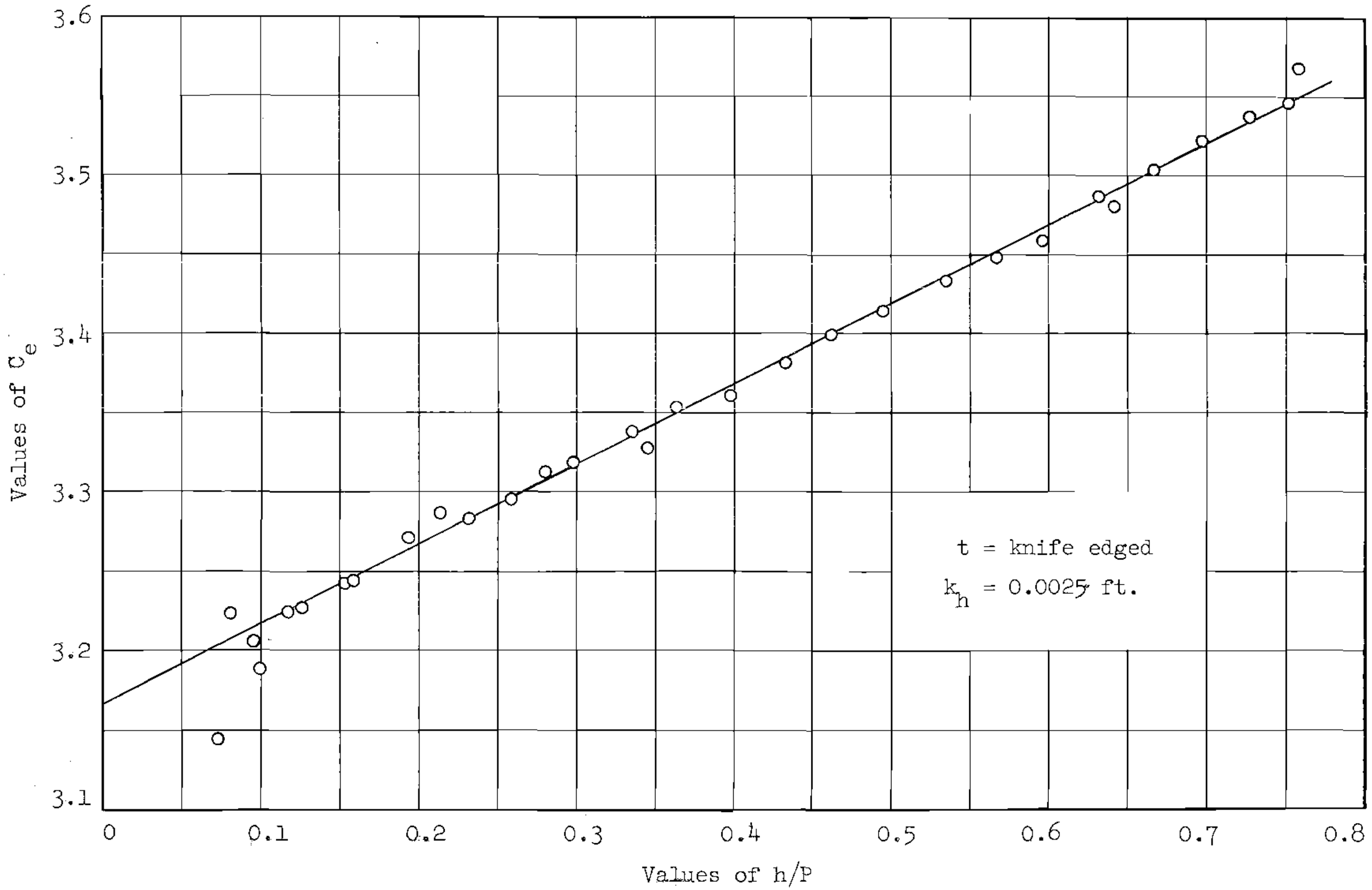

Fig. 23. C_e' as a Function of h/P, Test 11

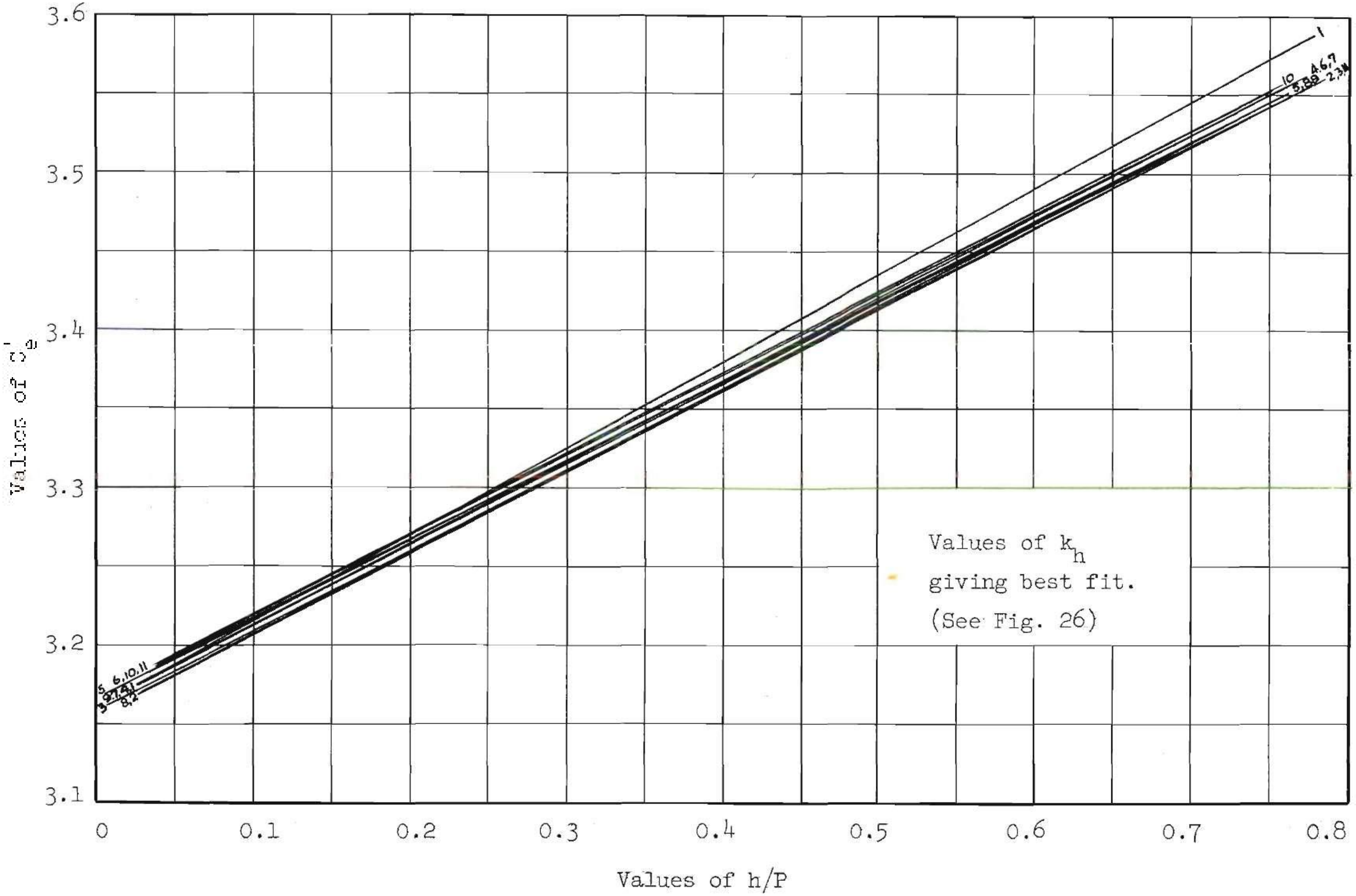

Figure 24. C_e' as Function of h/P, Best-Fit Values of k_h

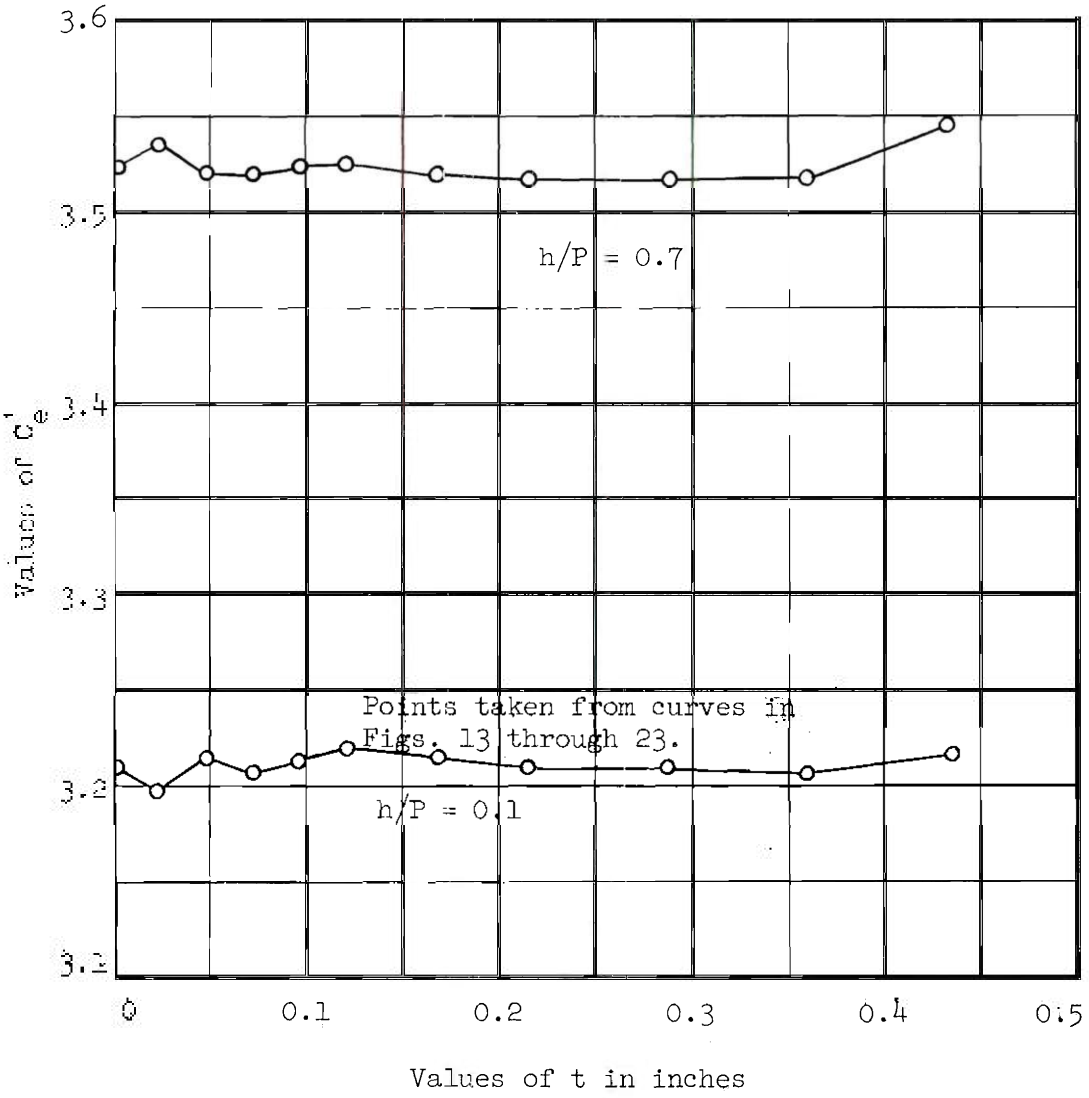

Figure 25. C_e' as Function of Crest Thickness

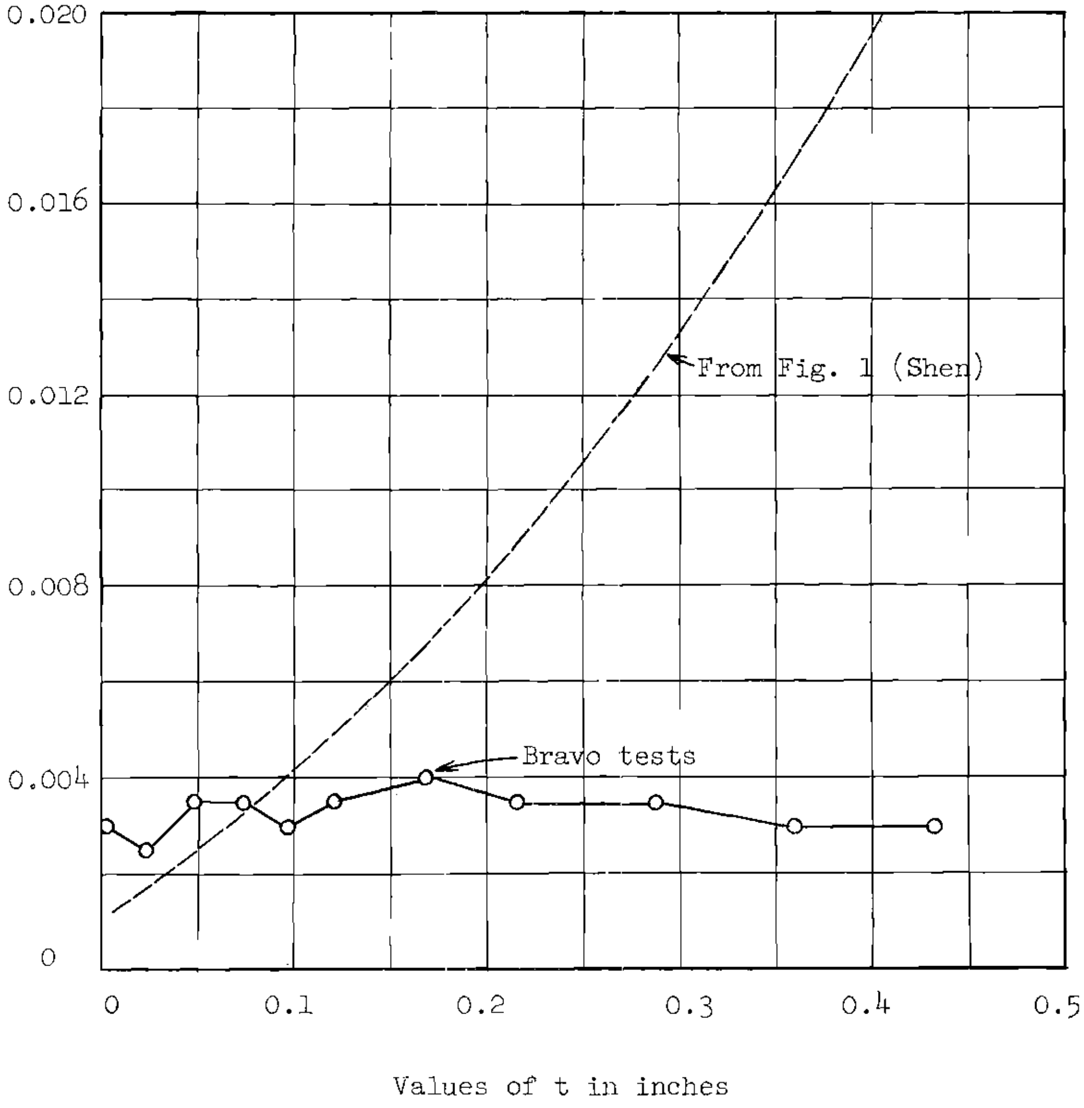

Figure 26. Comparison of k_h with Shen Curve

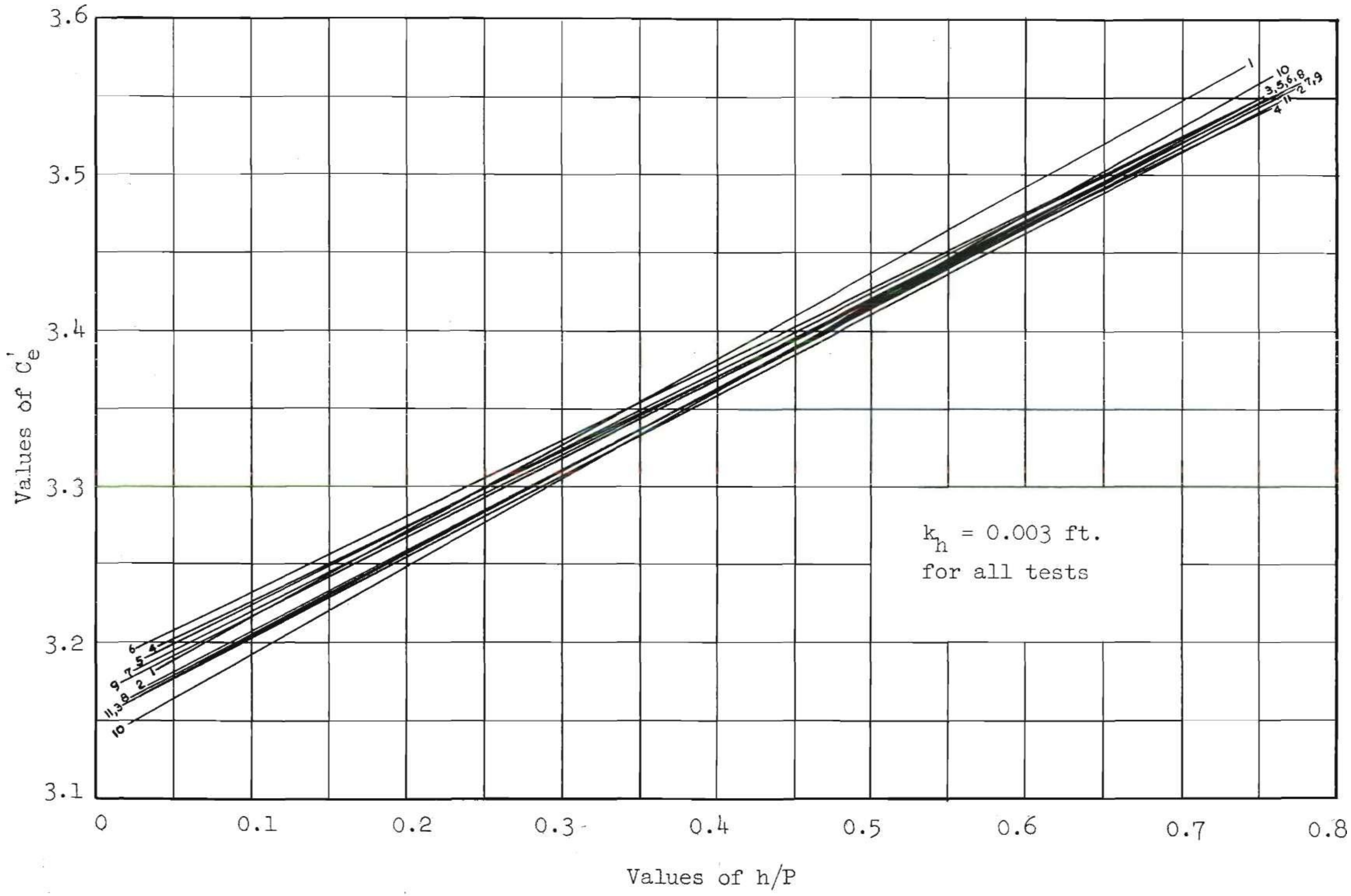

Figure 27. C_e' as Function of h/P, Constant Value of k_h

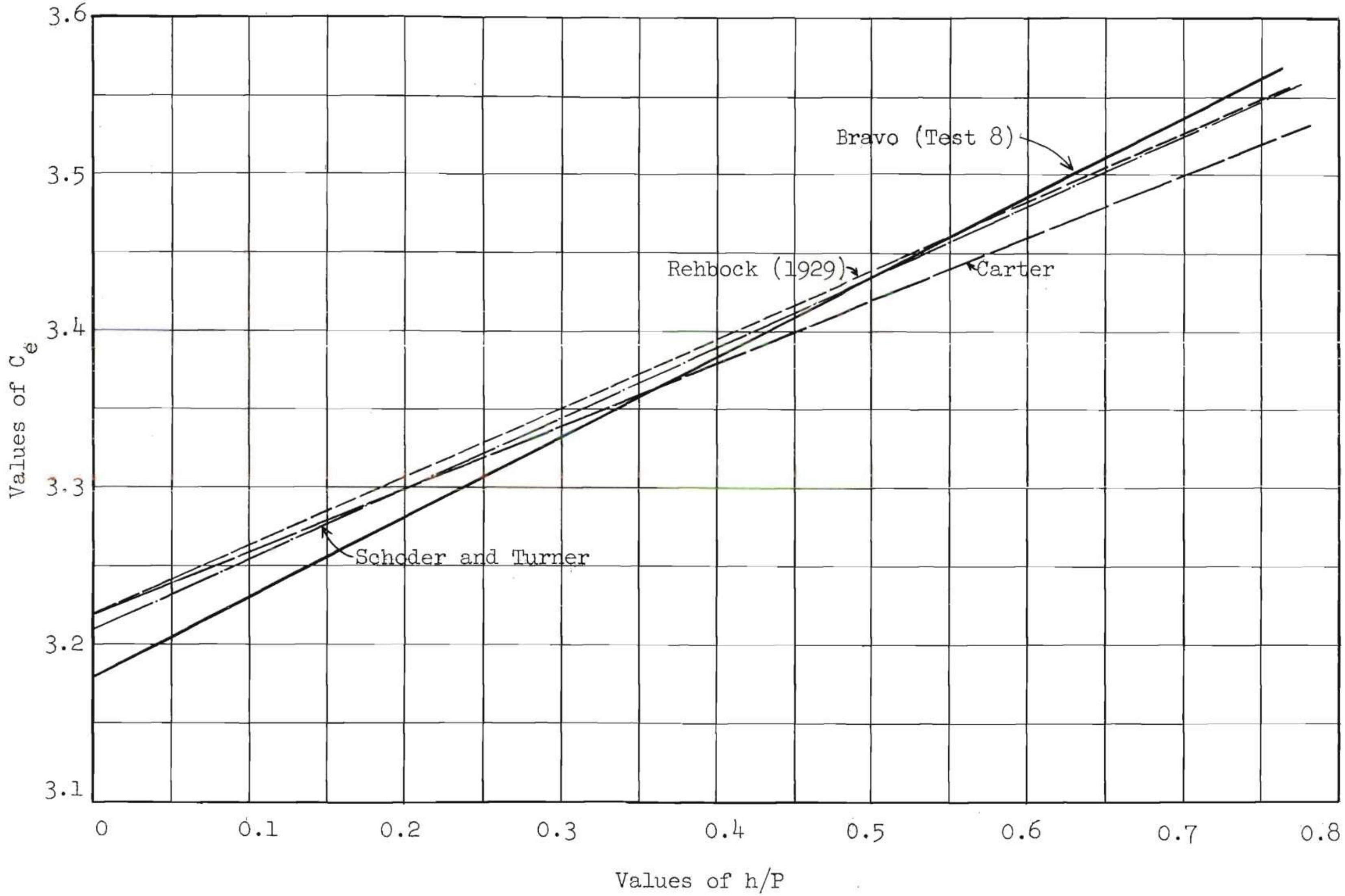

Figure 28. Comparison of Values of C_e from Different Investigations